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SMART STRUCTURES, AN OVERVIEW

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This report assesses the current status and maturity of smart structures technology. The report contains sections on smart materials, neural networks, health monitoring, and smart structures component technologies such as actuators, sensory elements, control methodologies and algorithms, controller architecture and implementation hardware, and signal conditioning and power amplification.

A strategic research and development plan is suggested for the Air Force. Eleven specific problems with Air Force aircraft structure and weapons systems are identified which have the potential for being alleviated or reduced by application of smart structures technologies.

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Contents

List of Figures

List of Tables

1. Introduction

Smart structures are those which contain actuators and sensors that are highly integrated into the structure and have structural functionality. In addition, smart structures contain highly integrated control logic, and signal conditioning and power amplification electronics. Actuating, sensing, and signal processing elements are incorporated into a structure for the purpose of influencing its states or characteristics (mechanical, thermal, optical, chemical, electrical or magnetic). A smart structure is capable of altering both its mechanical states (position or velocity) or its mechanical characteristics (stiffness or damping).

1.1 Definition of Smart Structures

Smart structures (also called intelligent structures in the astronautics field) are a minor subset of a much larger field of research, as shown in Figure 1.[1] Those structures which have actuators distributed throughout them are defined as adaptive. Definitive examples of such adaptive structures are conventional aircraft wings with articulated leading and trailing edge control surfaces, and robotic systems with articulated members. More advanced examples in current research include highly articulated adaptive space cranes. The subset of structures which have sensors distributed throughout them are referred to as sensory. These structures have sensors which might detect displacement strains; that is, mechanical properties, electromagnetic properties, temperature, or the presence or accumulation of damage. Applications of this technology might include damage detection in civil engineering structures, or in devices which are stored for long periods but must always be ready for action, such as rocket booster motors and so forth. The overlap of structures which contain actuators and sensors, and those which implicitly contain a closed-loop control system linking the actuators and sensors, are referred to as "controlled-structures." Any structure which has properties or states that can be influenced by the presence of a closed-loop control system are included in this category. A subset of controlled-structures are active structures. Active structures are distinguished from controlled-structures by highly distributed actuators which have structural functionality and are part of the load bearing system. Smart structures are a subset of active structures which have highly distributed actuator and sensor systems with structural functionality, and in addition, distributed control functions and computing architecture. To date, such smart structures have not been built. The realization of smart structures is a goal which has motivated this technology assessment, particularly for assessing the readiness of smart structures technology for incorporation into Air Force systems.

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[1]Wada, B.K., Fanson, J.L. and Crawley, E.F., "Adaptive Structures," J. of Intelligent Material Systems and Structures, Volume 1, April 1990, pages 157-174.

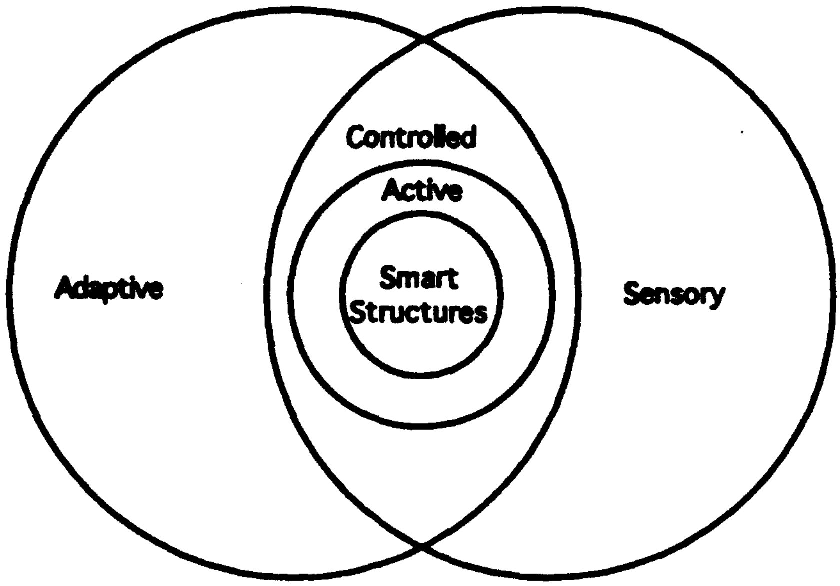

Figure 1: Smart structures are a subset of active and controlled structures

1.2 Development Background

There are three historical trends which have combined to establish the potential feasibility of smart structures. The first is a transition to laminated materials. In the past, structures were built out of large pieces of monolithic material which were machined, forged, or formed to a final structure making it difficult to imagine the incorporation of active elements. However, in the past thirty years, a transition to laminated material technology has occurred. Laminated materials, which are composed of smaller constitutive elements, allow for the easy incorporation of active elements which can alter the properties of the structure. Exploitation of the off diagonal terms in the material constitutive relations is a second trend which enables smart structures at this time. The full constitutive relations of a material include characterizations of its mechanical, optical, electromagnetic, chemical, physical and thermal properties. Nominally, researchers have focused only on block diagonal terms. For example, those interested in exploiting a material for its structural benefits have focused only on the mechanical characterization, and those interested in exploiting a material for its electrical properties focused only on the electrical characterization. Much gain can be made by exploiting the off block diagonal terms in the constitutive relations, which for example, couple the mechanical and electrical properties. It is in the characterization and exploitation of these off diagonal material constitutive relations that much of the progress has been made towards the creation of smart structures. The third, and perhaps most obvious advance comes in the electrical engineering and computer science disciplines. This includes the development of micro-electronics, bus architectures, switching circuitry, and fiber optic technology. Also central to the emergence of smart structures is the development of information processing, artificial intelligence and control disciplines. The sum of these three developing technologies, the transition to laminated materials, the exploitation of the off diagonal terms in material consti-

tutive relations, and the advances in micro electronics, have created the enabling infrastructure of technology in which smart structures can develop.

This report contains five additional sections; smart materials, smart structure component technologies, neural networks, health-monitoring, and a suggested research and development plan. Smart structures would not be possible without the development of smart materials or smart structure component technologies. Neural networks promise to allow a solution to very complicated problems. One possible way to improve methods for structural damage detection and health monitoring is through the use of smart material systems. A suggested research and development plan for the Air Force is presented at the end of this report.

2. Smart Materials

This section examines a class of materials, referred to as smart materials, which are able to interact with their environment (either as actuators or sensors or by altering their inherent properties) in some desirable manner. Smart materials are those from which smart material systems such as active or intelligent structures are constructed. In other words, smart materials are the constituent materials which make intelligent structures smart. To date, a tremendous amount of research has been performed in the areas of smart materials, intelligent structures, and smart material systems. Work has been performed in smart material development, characterization and modeling both for the materials themselves as well as for material systems and applications of intelligent structures, and several comprehensive papers have been written which summarize much of the work performed over the past decade.[2] [3] [4] [5] The objective of this section is to review the status and maturity of these materials from an applications point of view. Therefore, emphasis is placed on practical implementation issues and important details for designing systems which use smart materials. The smart materials assessed are piezoceramics, piezopolymer films, electrostrictives, magnitostrictives, shape memory alloys, and electrical-rheological fluids. The materials are assessed with respect to the fundamental issues important to smart materials, which are described in the first section of this report. The fundamental issues section is followed by a detailed assessment of the six smart materials listed above. This assessment is followed by a discussion of the current status of smart materials. A strategic research and development plan for smart materials is provided in the final section of this report.

2.1 Fundamental Issues

Before examining the properties of the smart materials listed above, it is essential to first define the important features of these materials and the issues relevant to assessing their usefulness in smart material systems applications. There are four fundamental issues relevant to the use of smart materials as elements of intelligent structures. These four issues can be described as component, effectiveness, usability, and implementation. It is important to fully consider each of these fundamental issues before selecting the materials to be used in particular applications. Each issue is further described below.

[2]Wada, B.K., Fanson, J.L. and Crawley, E.F., "Adaptive Structures," J. of Intelligent Material Systems and Structures, Volume 1, April 1990, pages 157-174.

[3]Rogers, C.A., "Intelligent Material Systems and Structures," Proceedings of the U.S.- Japan Workshop on Smart/Intelligent Materials and Systems, Honolulu, Hawaii, March 1990.

[4]Horner, C.G., Chairperson, "A State-of-the-Art Assessment of Active Structures," NASA TM 107681, NASA Langley Research Center, Hampton, VA, September 1992.

[5]Crawley, E.F., "Intelligent Structures," SDM Lecture, Presented at the 33rd Structures, Structural Dynamics and Materials Conference, Dallas, TX, April 1992.

2.1.1 System Components

The material selected for a particular component of an intelligent structure will depend, of course, on the application. However, some materials are better suited for some components than others because of their inherent properties. Most smart materials may be employed as one or both of the two fundamental components of intelligent structures. The two fundamental components are adaptive structures and sensory structures. Materials used for adaptive structural components (actuators) must be capable of altering the states of the intelligent structure. Actuator materials must be able to transfer energy into and out of the structure. On the other hand, materials used for sensory structural components (sensors) must be capable of monitoring the states of the system without (ideally) altering the energy in the system. Some materials are capable of both actuating and sensing, and some have the ability to perform these functions simultaneously.

2.1.2 Component Effectiveness

The ability of a material to meet the component functional requirements will depend on the effectiveness of the material specific to each application, and the effectiveness is often dictated by design-specific features such as component geometry. However, there are certain characteristics which are desirable in most cases. For actuator materials, these characteristics include the ability to generate large forces and displacements over large bandwidths. This requires materials with high elastic moduli, large actuation strains (high electro-mechanical coupling as defined by the strain constant d_{ij} and the ability to withstand high electric fields), and good linearity properties. In contrast, sensory materials should be compliant and are most effective when they have low elastic moduli, high electro-mechanical coupling as defined by the stress constants g_{ij}, and good signal-to-noise properties. Note that the strain constant is related to the stress constant by the dielectric properties of the material $d_{ij} = (K_i \varepsilon_o) g_{ij}$.

2.1.3 Usability for Particular Applications

Although a given smart material may make an effective component, certain properties may preclude its use for particular applications. Whether or not a material is usable for a given application usually is dictated by the operational environment. Effects such as temperature sensitivity, corrosion susceptibility, and moisture absorption must be considered during material selection. In addition, if the material is to be used for active control, other properties such as linearity and hysteresis must be considered as well.

2.1.4 Implementation Factors

When a particular design is to be fabricated and implemented, several other factors may be of consequence: weight limitations, the effect of limited isotropy, maximum

voltage and current levels, power consumption restrictions, effective bonding techniques, commercially available geometries and the ability to tailor geometries to specific needs, and a means for applying the required fields. Each of the above issues must be considered in selecting the material to be used for each smart material system component.

2.2 Comparison of Smart Materials

There are six types of smart materials examined in this report: piezoceramics, piezopolymers, electrostrictors, magnitostrictors, shape memory alloys and electrical-rheological fluids. These are the materials which have been most widely studied and used over the last decade, and are most readily available today through commercial suppliers. In this section, the mechanisms, models, properties, component functionality, and benefits and limitations of each are presented and discussed.

2.2.1 Piezoceramics

Piezoceramics are polycrystalline ceramics which are piezoelectric.[6] These materials are hard, dense ceramics which can be manufactured in many shapes and tailored to various applications. Piezoceramics are one of the most widely used smart materials in research and development and commercial applications. The most common type is made of Lead-Zirconate-Titanate (PZT), although other compositions are being developed and used for various applications.

MECHANISM

Piezoceramics exploit the piezoelectric effect. Piezoelectricity is the interaction between the electric field and mechanical strain caused by electrical monopoles within the material. The direct piezoelectric effect is the field created by the movement of the monopoles, while the indirect piezoelectric effect is the movement of the monopoles due to an applied electric field.[7] In order to make use of the piezoelectric effect, piezoceramics must be poled through the application of high electric fields. The field strength which poles, and re-poles, piezoceramics is known as the coercive field. Piezoceramics can also be de-poled by temperature. This temperature is defined as the curie temperature.

[6]Fleming, F. and Crawley, E.F., "Alternate Transducer Materials for Embedded Actuators in Intelligent Structures," SSL Report Number 2-89, Space Engineering Research Center, Massachusetts Institute of Technology, Cambridge, MA, 1989.

[7]Cross, E.L., "Polarization Controlled Ferroelectric High Strain Actuators," J. of Intelligent Material Systems and Structures, Volume 2, pages 241-260, July 1991.

MODELS

The fields E_i caused by applied strains and actuation strains Λ caused by applied fields are defined relative to the poling axis x_3 in piezoceramics. Field/strain coupling exists in the direction of poling and perpendicular to the poling direction as a result of Poisson's effect. The field is also coupled to the shear strain in some configurations. The fundamental relation of piezoelectricity between field and actuation strain is linear to first order:

$$\Lambda = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix}^T \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix} \qquad (1)$$

where d_{ii} is the electro-mechanical coupling coefficient and the superscript T denotes the transpose. In Equation 1 the first subscript defines the poling direction and the second subscript denotes the direction of strain. Although this relation is linear, it should be noted that a significant amount of non-linear effects are also present in these materials.

From a mechanical perspective, only the actuation strain defined in Equation 1 is needed to describe a structure with piezoceramic materials. The actuation strains are included in the constitutive relations in the same manner as other non-mechanical terms such as thermal strain and moisture absorption. The relations can then be simplified depending on the particular configuration. Such relationships have been developed for beams, [8] plates,[9] truss[10] and shell[11] elements of intelligent structures.

For a large number of applications (particularly those which use piezoceramics as actuators driven by prescribed fields) only these relations are needed. Thus, Equation 1 is just a simplified form of what is often called the "actuator equation." However for an accurate system description, the full electro-mechanical equations should be used. These relations include mechanical, electrical, and transformer terms. The full electro-mechanical equations, which combine to form coupled "actuator" and "sensor" equations, are detailed by Hagood, Chung and von Flotow.[12]

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[8]Crawley, E.F. and de Luis, J., "Use of Piezoelectric Actuators as Elements of Intelligent Structures," AIAA Journal, Volume 25, Number 10, October 1987, pages 1373-1385.

[9]Lazarus, K.B. and Crawley, E.F., "Induced Strain Actuation of Composite Plates," GTL Report Number 197, Massachusetts Institute of Technology, Cambridge, MA, 1989.

[10]Fanson, J.L., Blackwood, G.H. and Chu, C-C., "Active-Member Control of a Precision Structure," AIAA/ASME/ASCE/AHS 30th Structures, Dynamics, and Materials Conference, April 1989.

[11]Tzou, H.S. and Gadre, M., "Theoretical Analysis of a Multi-Layered Thin Shell Coupled with Piezoelectric Shell Actuators for Distributed Vibration Controls," J. of Sound and Vibration, Volume 132, Number 3, August 1989, pages 433-450.

[12]Hagood, N.W., Chung, W.H., von Flotow, A., "Modeling of Piezoelectric Actuator Dynamics for Active Structural Control," J. of Intelligent Material Systems and Structures, Volume 1, July 1990, pages 327-354.

PROPERTIES

Properties are listed in Table 1 for Navy Type II PZTs.[13] Several other PZTs are available, with properties that vary from those listed. However, the qualitative behavior of all PZTs are similar. Table 1 shows that piezoceramics have a high elastic modulus (roughly equivalent to that of aluminum), large bandwidth and moderate actuation strains (for strain actuators). These materials are fairly insensitive to temperature variations, but exhibit appreciable hysteresis and creep. In addition to hysteresis and creep, these materials behave in a non-linear manner as a result of a strain dependent coupling coefficient and limited isotropy.[14] Note that while the density is high compared to typical structural materials, it is roughly equivalent to the other strain actuators with high elastic moduli.

ASSESSMENT AND APPLICATION

The high modulus and moderate actuation strains of PZTs make these materials well suited for actuator components of intelligent structures. The use of piezoceramics as actuators is limited in some applications by piezoceramics' non-linearities, high density and moderate actuation strains. However, despite these drawbacks, their inherently high bandwidth make piezoceramics excellent actuators for dynamic applications. In addition, the amount of hysteresis and creep observed decreases with increasing bandwidth and decreasing strains,[15] and large actuation strains are usually not required at higher frequencies.

These features explain why the greatest interest in piezoceramic actuators has been in the fields of acoustic radiation[16] and adaptive optics[17] which generally require high frequency, small displacement actuators. However, PZT actuators have also been shown to be quite effective in other lower frequency, larger strain applications. PZT actuators have been successfully incorporated into active intelligent structures

[13]Piezo Systems Product Catalog, Piezo Systems, Inc., Cambridge, MA, 1990.

[14]Lazarus, Crawley, *op. cit.*

[15]Anderson, E.H., "Piezoceramic Induced Strain Actuation for One-and Two Dimensional Structures," S.M., Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1989.

[16]Clark, R.L. and Fuller, C.R., "Control of Sound Radiation with Adaptive Structures," J. of Intelligent Material Systems and Structures, Volume 2, July 1991, pages 431-452.

[17]Fanson, J.L., Anderson, E.H. and Rapp, "Active Structures of Use in Precision Control of Optical Systems," Optical Engineering, Volume 29, Number 11, 1990, page 1320.

for controlling trusses,[18] lifting surfaces,[19] [20] [21] aircraft cabins,[22] and rotor blades.[23] Recently piezoceramics have been applied to several commercial applications such as active mounts and suspension systems.[24]

2.2.2 Piezopolymer Films

Piezopolymers are pyroelectric transducers made from highly polar poly-vinylidene flouride films (PVDF). Piezopolymers obtain their piezoelectricity through a series of processing steps which include applying large strains, temperatures and voltages. The degree of electro-mechanical coupling achieved is highly dependent on these proprietary processes.[25] PVDF films have the highest piezoelectric and pyroelectric activities of all polymers. Piezopolymers are clear plastic films which can be readily cut and shaped in complex patterns.[26] This flexibility has enabled piezopolymers to be used as pressure and strain sensors in a large number of research and commercial applications.

Mechanisms

Piezopolymers function as a result of the same piezoelectric effect exploited by piezoceramics. However, piezopolymers act as sensors by exploiting the direct, rather than the indirect, piezoelectric. When used as a sensor, PVDFs develop a voltage on attached electrodes proportional to the applied load. This piezoelectric activity is created in piezopolymers by poling the material in the same manner as described for piezoceramics. There are three mechanisms which cause piezoelectricity in polymers. These are electrostriction, dimensional change, and inherent crystal

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[18]Fanson, Blackwood, and Chu, *op. cit.*

[19]Lazarus, K.B., Crawley, E.F and Lin, C.Y., "Fundamental Mechanisms of Aeroelastic Control with Control Surface and Strain Actuation," Proceedings of the 33rd SDM Conference, Baltimore, MD, April 1991, pages 1817-1831.

[20]Ehlers, S.M. and Weisshaar, T.A., "Static Aeroelastic Behavior of an Adaptive Laminated Piezoelectric Composite Wing," AIAA Paper Number 92-2626, 1992.

[21]Lazarus, K.B., "Multivariable High-Authority Control of Plate-Like Active Lifting Surfaces," Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1992.

[22]Sonti, V.R. and Jones, J.D., "Active Vibration Control of Thin Cylindrical Shells Using Piezo-Electric Actuators, Proceedings of the Conference on Recent Advances in Active Control of Sound and Vibration," Virginia Polytechnic Institute and State University, Blacksburg, VA, 1991.

[23]Spangler, R.L., "Piezoelectric Actuators for Helicopter Rotor Control," S.M. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1989.

[24]Newnham, R.E. and Ruschau, G.R., "Smart Electroceramics," J. of the American Ceramic Society," Volume 74, Number 3, March 1991.

[25]Collins, S.A., Miller, D.W., von Flotow, A.H., "Sensors for Structural Control Applications Using Piezoelectric Polymer Film," SERC Report Number 12-90, Massachusetts Institute of Technology, Cambridge, MA, 1990.

[26]Kynar Piezo Film Product Catalog, Elf ATOChem, Kynar Piezo Film Department, Valley Forge, PA, 1991.

Table 1: Important properties of smart materials

Material Property	**Units**	**PZT**[a]	**PVDF**[b]	**PMN**[c]	**Terfenol**[d]	**SMA**[e]
Young's Modulus, E	GPa	62	2.0	117	30	30 / 89[j]
Yield or Ult. Strength	MPa	70	140-210	21	28	74 / 670
Strain Constant, d_{33}	$\frac{m}{V}$ x 10^{12}	360	-33	285[h]	i	-
Stress Constant, g_{33}	$\frac{m}{C}$ x 10^{3}	25	-339	-	-	-
Dielectric Constant	$\frac{\varepsilon}{\varepsilon_0}$	1700	12	26,000	-	-
Coercive or Max. Field	$\frac{V}{\mu m}$	1.2	30	2.0	-	-
Max. Actuation Strain	%	0.09[g]	0.1	0.1	0.18	2.0-8.0
Curie or Activation Temp.	°C	360	100[f]	200[e]	380	$\frac{41}{77}$[k]
Density	$\frac{kg}{m^3}$	7600	1780	7800	9250	6500
Coef. of Thermal Exp.	$\frac{ppm}{°C}$	5	-	1.0	12	$\frac{6.6}{0.11}$
Gain-Temp. Sensitivity	$\frac{\%}{°C}$	0.05[f]	0.8[f]	3.0	0.3[f]	
Resistivity	Ohm-m	$1e^8$	$1e^13$	$1e^8$	$6e^{-7}$	$\frac{8e^{-7}}{10e^{-7}}$
Hysteresis	%, 1 Hz	10	15-20	1.5	2.0	5.0
Aging or Creep	-	Moderate	Moderate	Low	Low	Moderate
Bandwidth	cycles/s	KHz	KHz	KHz	100 Hz	1 Hz

Notes:

(a) Values taken from Piezo Systems[27] catalog unless otherwise noted.
(b) Values taken from Kynar Piezo Film[28] catalog unless otherwise noted.
(c) Values taken from Blackwood and Ealey[29] unless otherwise noted.
(d) Values taken from Etrema Products[30] catalog unless otherwise noted.
(e) Values taken from Fleming and Crawley[31] unless otherwise noted.

[27] Piezo Systems Product Catalog, Piezo Systems, Inc., Cambridge, MA, 1990.

[28] Kynar Piezo Film Product Catalog, Elf ATOChem, Kynar Piezo Film Department, Valley Forge, PA, 1991.

[29] Blackwood, G.H. and Ealey, M.A., "Characterization of Electrostrictive Behavior in Lead Magnesium Niobate (PMN) Actuators at Low Temperatures," submitted to Ferroelectrics, January 1992.

[30] "ETREMA Terfenol-D Magnetostrictive Actuators," Etrema Products Division, Edge Technologies, Inc., Ames, Iowa, 1992.

[31] Fleming, F. and Crawley, E.F., "Alternate Transducer Materials for Embedded Actuators in In-

(f) Values taken from Horner.[32]
(g) Values taken from Lazarus and Crawley.[33]
(h) Value calculated at 0.55V/mm.
(i) A discussion of the strain/magnetic field coupling constant is given in Verhoeven.[34]
(j) Martensite / Austenite values.
(k) Martensite finish / Austenite finish temperatures.

piezoelectricity.[35] In piezopolymers, dimension change is the dominant contributor to the electro-mechanical coupling coefficient.

MODELS

The same basic field/strain relationship (Equation 1 and the aforementioned higher order models) governs the transfer of electrical and mechanical energy in piezopolymers. However, these relations can be expressed in forms more convenient for sensing applications where the desired relationship is that between the structural strain and resulting charge developed on the electrodes and is indicated by the symbol e_{ij}. This strain/charge relation has been developed by Lee[36] for two-dimensional structures and is often referred to as the "sensor" equation. For a piezopolymer poled through the thickness (x_3) and strain in one transverse direction (x_1) this relation reduces to

$$e_{31} = (d_{31} + v d_{32}) \frac{E}{1 - v^2} \tag{2}$$

where d_{ij} is the electro-mechanical coupling coefficient, E is the elastic modulus and v is Poisson's ratio.[37] Note that this is a very common configuration for piezopolymer sensors, and the voltage on the sensor electrodes can be found simply by dividing the charge by the capacitance of the sensor.

PROPERTIES

Properties are listed in Table 1 for the most commonly used piezopolymer film known as PVDF. These materials are flexible and lightweight. Piezopolymers have a modulus one-thirtieth and a density of one-fourth of PZTs. PVDF has a high dielectric constant which allows for the application of high voltages, however a low modulus and electro-mechanical coupling coefficient prevent the use of these materials as actuators

telligent Structures," SSL Report Number 2-89, Space Engineering Research Center, Massachusetts Institute of Technology, Cambridge, MA, 1989.

[32]Horner, C.G., Chairperson, "A State-of-the-Art Assessment of Active Structures," NASA TM 107681, NASA Langley Research Center, Hampton, VA, September 1992.

[33]Lazarus, K.B. and Crawley, E.F., "Induced Strain Actuation of Composite Plates," GTL Report Number 197, Massachusetts Institute of Technology, Cambridge, MA, 1989.

[34]Verhoeven, J.D., et.al., "Directional Solidification and Heat Treatment of Terfenol-D Magnetostrictive Materials," Metallurgical Transactions, Volume 21A, August 1990, pages 2249-2255.

[35]Wada, Y. and Hayakawa, R., "A Model Theory of Piezo- and Pyroelectricity of Poly (vinylidene Fluoride) Electret," Ferroelectricity, Volume 32, Number 1-4, 1981, pages 115-118.

[36]Lee, C.K., "Laminated Piezopolymer Plates for torsion and Bending Sensors and Actuators," J. Acoustical Society of America, Volume 85, Number 6, 1989, pages 2432-2439.

[37]Collins, Miller, von Flotow, *op. cit.*

in most applications. As with most viscoelastic polymers, PVDF has high loss factor with a loss tangent of about 10%.[38] This is a benefit in terms of passive damping, but a hindrance for active control. The properties of piezopolymers are highly dependent on temperature. In addition, the electro-mechanical coupling coefficient decays faster over time as the temperature increases. Note that this effect is negligible at room temp, but becomes pronounced at temperatures above 60°C.[39]

Assessment and Application

Although the low modulus often precludes use of piezopolymers as actuators, their high field tolerance and electro-mechanical coupling yield high actuation strains that could make effective actuators in applications where obtaining a good mechanical impedance match is possible. Regardless, there is no doubt that these materials make excellent sensors due to their low modulus and weight. These features make their effect on the dynamics of intelligent structures very small. Plus PVDF films can easily be shaped into many geometries which allow for flexible and unobtrusive use in many sensing applications. Further, piezopolymers are capable of sensing over large frequency ranges. These materials are also relatively inexpensive and require little conditioning electronics. Finally, piezopolymers have acoustic impedances near that of water and human tissue which limit acoustic radiation and make for excellent signal response in relevant applications.

These favorable properties have allowed piezopolymers to be used in countless applications. Many of these are outlined in the ATOChem Technical Manual and described by Sessler.[40] Some of these applications include non-destructive testing, optical and keyboard sensors, ultrasonic imaging, and hydrophonic measurement. In addition, there have been many applications of PVDF sensors for active control of intelligent structures. An excellent review of this field is given by Collins, Miller, and von Flotow.

2.2.3 Electrostrictives

Electrostrictives are materials which change dimensionally due to an applied electric field as do piezoceramics and piezopolymers. However, the actuation strains developed in electrostrictives result from an interaction between electric fields and electric dipoles (rather than monopoles) in the material. Common electrostrictive materials include Lead-Magnesium-Niobate (PMN) and Lead-Lanthanum-Zirconate-Titanate (PLZT), with PMN being the most widely used,[41] especially in the area of precision optics.[42]

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[38]Kynar, *op. cit.*

[39]Collins, Miller, and von Flotow, *op. cit.*

[40]Sessler, G.M., "Piezoelectricity in Polyvinylideneflouride," J. of the Acoustical Society of America, Volume 70, Number 6, 1981, pages 1567-1576.

[41]Uchino, K., "Electrostrictive Actuators: Materials and Applications," American Ceramic Society Bulletin, Volume 65, Number 4, 1986, pages 647-652.

[42]Horner, *op. cit.*

MECHANISMS

In contrast with PZTs and PVDFs, electrostrictives self-polarize and therefore do not require initial polarization. The application of a field to electrostrictives causes an alignment of randomly oriented electric dipoles in the material. As a result, the material deforms (strains). The material continues to strain as the field increases and a greater percentage of the dipoles become aligned. Maximum strain is achieved when all dipoles are aligned, causing the electrostrictive effect to be saturated.

MODELS

Since electrostrictives are self-polarizing the material strains (due to electrostriction) only in the direction of the applied field. Of course, the material will also strain in the transverse directions due to Poisson's effect. The strains created in the material are modeled as a quadratic function of the applied field[43]

$$\Lambda = \begin{bmatrix} m_{33} & m_{31} & m_{31} & 0 & 0 & 0 \\ m_{31} & m_{33} & m_{31} & 0 & 0 & 0 \\ m_{31} & m_{31} & m_{33} & 0 & 0 & 0 \end{bmatrix}^T \begin{Bmatrix} E_1^2 \\ E_2^2 \\ E_3^2 \end{Bmatrix} \tag{3}$$

where m_{ii} is the electro-mechanical coupling (strain) coefficient and the superscript T denotes the transpose. In Equation 3, the first subscript defines the direction of applied field and the second subscript denotes the direction of strain. Although this simple model is used in most applications, these materials are nonlinear and not accurately modeled by the simple relation presented above. The most dominant nonlinear effect on the coupling coefficient in electrostrictives is due to the strain dependence of the dielectric properties. Little attempt has been made to model the inherent nonlinearities in electrostrictives. Electrostrictive actuators typically use bias voltages to operate in approximately linear regions (reducing the useful actuation strain from 0.2% to ±0.05% for a bias of 0.40V/mm and an alternating field of ±0.30V/mm).[44]

PROPERTIES

Electrostrictives have a very high modulus of 117 GPa and develop actuation strain similar to those found in piezoceramics. Because these materials are not poled, there is no coercive field. Therefore, a strain saturation field of 2V/mm is reported in Table 1. Further, the strain coupling coefficient is not constant but a function of field so the value reported is the maximum value which occurs at 0.55V/mm. At moderate temperatures and low frequencies electrostrictives exhibit remarkably low level of hysteresis and creep. But, nearly every property of electrostrictive materials

[43]Anderson, E.H., Moore, D.M., Fanson, J.L. and Ealey, M.A., "Development of an Active Truss Element for Control of Precision Structures," Optical Engineering, Volume 29, Number 11, November 1990, pages 1333-1341.

[44]Blackwood, G.H. and Ealey, M.A., "Characterization of Electrostrictive Behavior in Lead Magnesium Niobate (PMN) Actuators at Low Temperatures," submitted to Ferroelectrics, January 1992.

is temperature dependent, including the strain coupling coefficient, hysteresis and loss, and field required for strain saturation. Blackwood and Ealey[45] observed a marked decrease in actuation strain and increase in hysteresis as the temperature was changed from the design operating temperature of 25°C. The same undesirable effects on actuation strain and hysteresis were also found to occur as the driving frequency increased.

ASSESSMENT AND APPLICATION

The greatest advantage of electrostrictives is their virtual lack of hysteresis and creep at low frequencies and moderate temperatures due to the absence of permanent polarization.[46] This gives these materials excellent set point accuracy, which makes these actuators ideal choices for low frequency precision positioning and pointing. Thus, electrostrictive actuators have been used extensively in positioning and deforming mirrors for precision adaptive optics applications.[47] Electrostrictives have also been explored as alternatives to piezoceramics in active strut applications.[48] However, despite such favorable features, the degradation of strain coefficient and hysteresis properties at higher frequencies limits the useful bandwidth of electrostrictives actuators. Further, a high dielectric coefficient (resulting in a high capacitance) further limits the usefulness of these materials in higher frequencies.

2.2.4 Magnetostrictives

Magnetostrictive materials are the magnetic analogy to electrostrictives. Ferromagnetic materials, or magnitostrictors, strain as a result of the interaction between applied magnetic fields and magnetic dipoles in the material. Materials with magnetic monopoles do not exist. Many rare earth elements have good magnetostrictive properties. The most common magnetostrictor is composed of Terbium, Dysprosium and Iron and is known as Terfenol-D (Ter-Terbium, Fe-Iron, Nol-Naval Ordinance Laboratory, D-Dysprosium).[49] Magnetostrictors have high electro-mechanical coupling coefficients and can be used as both actuators and sensors.

MECHANISMS

Similar to electrostrictors, the actuation strain found in magnetostrictors is a function of the applied field squared. Magnetic fields cause randomly distributed magnetic dipoles to rotate and align in the field direction. The dipole rotation produced strain in the material. As the field increases, more dipoles become aligned with the field

[45] Blackwood, and Ealey, *op. cit.*

[46] Fleming and Crawley, *op. cit.*

[47] Ealey, M.A., "Active and Adaptive Optical Components: A General Overview," Proceedings of the Conference on Active Materials and Adaptive Structures, IOP Publishing, Ltd., 1992.

[48] Anderson, Moore, Fanson, and Ealey, *op. cit.*

[49] Fleming and Crawley, *op. cit.*

and the strain increases until all the dipoles are aligned and the effect is saturated. Magnetostrictives self-polarize and therefore do not require initial polarization.

Models

The strains produced by the magnetostrictive effect are a function of the applied field squared

$$\Lambda = kH^2 \tag{4}$$

where k is the magneto-mechanical coupling and H is the magnetic field. Typically, the magnetic fields are created by a solenoid. The magnetic field is related to the current in the solenoid by

$$H = nI \tag{5}$$

where n is the number of turns per unit length. The voltage needed to drive the actuator can then be determined simply by multiplying the required current by the coil resistance. A bias magnetic field is used to operate magnetostrictor actuators in a bi-directional, quasi-linear fashion, as described above for electrostrictors. This lowers the useful actuation strain from roughly 0.2% to 0.1%.

Properties

The properties of magnetostrictives are well suited by actuator applications. This material has an elastic modulus of roughly 60 Gpa and is capable of producing actuation strains of up to 0.2%. In addition, magnetostrictives exhibit low hysteresis and are relatively insensitive to temperature variations.

Assessment and Application

Magnetostrictives produce greater actuation strains when pre-stressed.[50] This appealing feature simplifies the actuator design process. Other attractive features of magnetostrictive materials include a relatively high modulus and large actuation strains. The bandwidth of these materials is limited by mechanical resonances as well as magnetic eddy currents, however these materials respond quickly enough to satisfy most actuator requirements.[51] Most applications for magnetostrictive actuators remain in the research arena. Investigators are assessing their use for optical bench damping, gimbaling, cockpit simulators and aeroelastic control surfaces.[52] Although magnetostrictive linear potentiometers have recently been introduced by MTS Systems, Inc., the biggest drawback with magnetostrictive materials are the difficulties associated with applied magnetic fields. Problems applying magnetic fields for spatially distributed or modulated actuators limit the use of magnetostrictives in intelligent structures.

[50]"ETREMA Terfenol-D Magnetostrictive Actuators," Etrema Products Division, Edge Technologies, Inc., Ames, Iowa, 1992.

[51]Fleming and Crawley, *op. cit.*

[52]Horner, *op. cit.*

2.2.5 Shape Memory Alloys

The ability to recover a particular shape when activated by an external stimulus is known as the shape memory effect. Nitinol (Ni-Nickel ti-Titanium, nol-Naval Ordinance Laboratory), which is activated by the application of heat, is the most widely known shape memory material. This alloy is capable of recovering very large (2-8%) strains during its martensite to austenite transformation. This transformation results in a significant change in elastic modulus.

MECHANISMS

The shape memory effect is qualitatively different from the other actuating mechanisms described above. This phenomenon is created by a material phase change between martensite and austenite as a result of heating. Associated with the phase change are material deformation and strain. The shape memory effect allows for shape recovery of martensitic deformations (up to 8% strain) when heated to the austenite phase. Recovery begins at the austenite start temperature A_s and is completed at the austinite finish temperature A_f. In most applications a bias force is used to create two way motion. However, it is possible to process Nitinol to have a two way effect, but the actuation strains are limited to 2% in such cases. Some applications also take advantage of other shape memory alloy effects such as pseudoelasticity. A detailed discussion of the shape memory effect can be found in Liang and Rogers.[53]

MODELS

At a very basic level the actuator equation (Equation 1) can be used to model the shape memory actuation strain. In this case the coupling coefficient d_{ij} would relate the temperature change (rather than applied field) to actuation strain. However, in almost all real applications such a simple relation is insufficient and a more accurate model is needed. A detailed thermo-mechanical model was developed by Tanaka and Nagaki[54] and a multi-dimensional constitutive model was reported by Liang and Rogers.[55] Although these models are fairly accurate, the full nonlinear thermomechanical behavior of these unique materials can only be described accurately by including non-equilibrium thermostatics relations. Such a complex model is offered by MacLean, Patterson and Misra.[56] One small element of this model describes the

[53]Liang and Rogers, *op. cit.*

[54]Tanaka, K. and Nagaki, S., "A Thermomechanical Description of Material with Internal Variables in the Process of Phase Transformation," Ingenieur-Archiv, Volume 51, 1982, pages 287-299.

[55]Liang, C. and Rogers, C.A., "Design of Shape Memory Alloy Coils and Their Applications in Vibration Control," Proceedings of the Second Joint Japan/U.S. Conference on Adaptive Structures, Nagoya, Japan, November 1991, pages 177-198.

[56]MacLean, G.J., Patterson, G.J. and Misra, M.S., "Modeling of a Shape Memory Integrated Actuator for Vibration Control of Large Space Structures," Proceedings of the Conference on Recent Advances in Active Control of Sound and Vibration, Virginia Polytechnic Institute and State University, Blacksburg, VA, 1991.

resistive heating and cooling which activates shape memory materials. The time constant τ associated with heating and cooling of these elements of intelligent structures is

$$\tau = \frac{mc}{hA} \tag{6}$$

where m is the mass, c is the specific heat, A is the surface area of the component, and h is the heat transfer coefficient.[57]

Properties

Shape memory alloys (SMAs) possess a high modulus and are capable of large actuation strains (2%-8%). The elastic modulus is shown in Table 1 to be 30 GPa in the martensite phase and 89 GPa in the austenite phase. Shape memory alloys also have ultimate strength and fracture toughness properties which are far superior to other actuator materials. However, the temperature sensitivity is quite high (as expected), they are quite hysteretic, and can operate only in very low frequency regimes because of limitations imposed by the second law of thermodynamics.

Assessment and Application

The high force and large stroke capability of shape memory alloys make them excellent actuator materials. However, their strong temperature sensitivity and high hysteresis limit the use of these materials to applications which require large motions but do not need an extremely high degree of precision (unless the environment allows for precise temperature control). Shape memory alloys are commonly used in the form of wires which are heated through resistive heating and cooled through surface convection.[58] Other popular forms for this material include conventional spring, tubes, and thin plates. Many investigators have examined the use of shape memory materials embedded as elements of laminated composites. Composite shape memory alloys have obvious advantages from a mechanical perspective, however cooling rates of embedded SMAs are reduced significantly, further lowering the response time of these materials. Although shape memory alloys have been used in a wide variety of commercial applications including fog light louvers, coffee makers, orthodontic wire, and medical devices,[59] their application is limited by their inherently low bandwidth.

2.2.6 Electrical-Rheological Fluids

Electrical-Rheological (ER) fluids are a fundamentally different type of smart material. ER fluids are made of viscous fluids and fine particle suspensions which react to applied electric fields that alter the properties of the material. Intelligent structures with ER fluids provide the capability for altering the material damping properties. The most common ER fluids are composed of silicon oil and corn starch.

[57] Fleming and Crawley, *op. cit.*

[58] "Flexinol Actuator Wires," Dynalloy, Inc., Irvine, CA, 1992.

[59] "Furukawa NT Alloys," Furukawa Electric Co., Ltd., Tokyo, Japan, 1992.

Mechanisms

Intelligent structures which make use of this smart material are able to alter their damping properties due to the variable viscosity of ER fluids. The mechanism which allows ER fluids to have variable viscosity results from the interaction between applied electric fields and particles suspended within the fluid. The particles, which have polarizable dielectric constants are suspended in a hydrophobic (dielectric) liquid. The electric field causes an alignment of the particle in the fluid. In the absence of applied electric fields, ER fluids exhibit Newtonian flow characteristics. However, when electric fields are applied, the ER fluid viscosity increases rapidly. Further, at high fields and low stresses these smart fluids begin to behave like solid materials in terms of possessing a definable yield strength.

Models

Currently, models of intelligent structures with ER fluid components have not been well developed. However, simple models of their behavior can be formulated. The basic phenomenon to be modeled is the shear stress created by a surface moving over an ER fluid. Such terms appear in the equations of motion as rate dependent damping. For Newtonian fluids the shear stress τ is equal to the viscosity μ times the shear strain rate

$$\tau = \mu \frac{du}{dy} \tag{7}$$

where the viscosity is a property of the fluid and is constant. However, for an ER fluid, the viscosity becomes a function of the applied field. In addition, a variable stiffness (also a function of applied field) term can be used to model the load carrying ability of some ER fluids with high fields applied. Currently, these variable damping and stiffness terms must be found empirically for each particular fluid to be used.

Properties

ER fluids are an entirely different type of smart material than the others examined in this report. These materials have neither well defined elastic moduli or actuation strains, and were therefore not included in the material properties table. In addition, the materials themselves have not been well categorized. Regardless, a good estimate of the viscosity of an ER fluid is needed for application design, and this property must be known as a function of applied field. Currently, the most popular ER fluid is made of a mixture of 65% silicon oil and 35% corn starch. This ER fluid has been shown to increases in viscosity by 40% with an applied field of 4V/mm.[60]

[60]Yu, W.-C., Kanu, R. and Shaw, M.T., "Design of Anhydrous Electrorheological (ER) Suspensions and Mechanism Study," Proceedings of the Active Materials and Adaptive Structures Conference, Alexandria, VA, November 1991, pages 757-760.

The mechanical arrangement is a fluid sandwiched between two opposing walls. Such systems have been used for clutches, engine mounts, high speed valves and active dampers.[61] The advantage of using an ER fluid in these applications is that the viscosity can be actively changed so that maximum damping is applied to a particular mode or modes. Thus, devices can be tuned to be most effective for some given operating condition (RPM, type of terrain, or disturbance frequency). Although this is sometimes referred to as active tuning, what is actually being accomplished is best described as changing the passive damping characteristics of the system. On the other hand, ER fluids do respond quickly enough to be used in true active control applications, but work in this area is only in the early development stages.

2.3 Current Status

As noted in previous discussions, there are many types of smart materials to be considered for various applications. For example, actuator applications which require large strains are best suited for shape memory alloys unless fast response times are needed. Large strains and high bandwidth needs may be satisfied with magnetostrictives unless the particular configuration precludes the application of magnetic fields, in which case piezoceramics or electrostrictives become attractive alternatives. In addition, other factors such as environment, power limitations and weight constraints must be considered in each particular intelligent structure design. Thus, there is no clear choice of "best" smart material, and a great deal of research and development effort is being expended in this field.

2.3.1 Research and Development

Currently, smart material research and development can be categorized into two broad classes, the first being the research into creating better materials and the second being the development of innovative smart material devices. Most of the effort associated with piezoelectric materials is focused on developing materials with larger actuation strains.[62] However, materials which produce large strains are highly nonlinear and have poor mechanical properties (fatigue strength and stress cracking). Much work is also being done to avoid these problems such as the development of piezoelectric composites. Piezoelectric composites have improved mechanical properties but poor dielectric properties, which makes it difficult to apply the necessary electric fields. Much basic research is also being done on ER fluids to create materials with enhanced electrical-rheological properties. The amount of effort expended in the development of smart material devices has recently increased dramatically. Most of this work involves the development of devices which multiply the actuation strains developed, increases the ease in which fields are applied, or reduces the fields required. For example, the

[61] Horner, *op. cit.*
[62] Cross, *op. cit.*

recently developed "Moonie" actuator[63] increases piezoceramic strokes by a factor of five and for multilayer piezoceramic and electrostrictive stacks reduces required voltages by orders of magnitude. Also, research in areas such as modal actuators[64] and sensors[65] add significantly to the usefulness of smart materials. It is expected that the amount of work being performed in device development will continue to accelerate.

2.3.2 Commercial Availability

The ongoing research and development work is supported by a growing infrastructure of commercial suppliers. All of the materials described in this report are commercially available. Most are available in a variety of types (plates, disks, tubes, bimorphs and stacks), shapes, and sizes. In addition, these suppliers often lead or sponsor much of the material development work. Many of these firms have been rewarded for their efforts and enjoy a dominant position in their respective markets (as a result of patents, trade secrets and clever marketing). A partial list of the major smart material suppliers is included below. The asterisk indicates a company with a dominant position in the marketplace.

Piezoceramics

American Piezo Ceramics, Inc., Mackeyville, PA, USA.

EDO Corporation, Western Division, Salt Lake City, UT, USA.

Keramos, Inc., Indianapolis, IN, USA.

Morgan Matroc, Inc., Vernitron Division, Bedford, OH, USA.

Piezo Kinetics, Inc., Bellefonte, PA, USA.

Piezo Systems, Inc., Cambridge, MA, USA.

Piezopolymers

*Elf ATOChem Sensors, Inc., Kynar Piezo Film Division, Valley Forge, PA, USA.

Electrostrictives

AVX Inc., Corporate Research, Conway, SC, USA.
Litten/Itek Optical Systems, Lexington, MA, USA.

Magnetostrictives

*EDGE, Technologies, Inc., ETREMA Products Division, Ames, Iowa, USA.

Shape Memory Alloys

Dynalloy, Inc., Irvine, CA, USA.

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[63] Uchino, *op. cit.*
[64] Lee, *op. cit.*
[65] Collins, Miller and von Flotow, *op. cit.*

Furukawa Electric Co., Ltd., Tokyo, Japan.
Shape Memory Applications, Inc., Sunnyvale, CA, USA.

Electrical-Rheological Fluids

All major automotive centers and supermarkets.

3. Smart Structure Component Technologies

There are five component technologies critical to the evolution and application of smart structures to near-term Air Force concerns. These five component technologies are:

- Actuators for Smart Structures
- Sensory Elements
- Control Methodologies and Algorithms
- Controller Architecture and Implementation Hardware
- Signal Conditioning and Power Amplification

3.1 Actuators for Smart Structures

Actuators for smart structures must be capable of high distribution and influence on the mechanical states of the structure. Ideal strain actuators directly convert electrical inputs to strain in the host structure. Therefore, the primary performance parameters include maximum achievable stroke or strain, stiffness, bandwidth and power requirements. Secondary performance parameters include linearity, property fluctuation with operating environment, temperature sensitivity, strength and density. These properties will be assessed and compared for several types of strain actuators. In addition, the availability of each actuator type will be considered.[66] Currently, many types of strain actuators are available, including piezoceramics, piezoelectric films, electrostrictives and shape memory alloys.

The principal actuating mechanism of strain actuators is referred to as actuation strain. Actuation strain is the strain which is controllable and not due to stress. Actuation strains are produced by a variety of phenomenon, with the most common but least controllable being temperature and moisture absorption. Other examples, which are less common but more useful for active control, include piezoelectricity, electrostriction, magnetostriction, and the shape memory effect. The latter four phenomenon are desirable actuating mechanisms since they directly convert electrical signals into actuation strain.

3.1.1 Strain Actuator Modeling

The actuation strain enters into the constitutive relations in the same manner as does commonly modeled thermal strains. The constitutive relations dictate that the total strain in the actuator material is the sum of the mechanical strain, induced

[66]Ealey, M.A., "Actuators: Design Fundamentals, Key Performance Specifications, and Parametric Trades," Proc. of the SPIE Conference on Active and Adaptive Optical Systems, 15433-32 (1991).

by the stress, plus the controllable actuation strain. Once the strain is induced in the actuator, it must be converted to strain in the host structure. The strain in the host structure can be found from a number of different assumptions about the local strain deformation field. The simplest assumption for a surface mounted actuator is that of uniform strain in the actuation material, and linearly distributed strain throughout the host structure. Such a model is not very exact, but is useful for obtaining simple figures of merit by which actuators can be compared. The most useful and general model is the Bernoulli-Euler Kirchoff assumption, in which the strain is linearly distributed throughout the actuator and host structure regardless of whether the actuator is surface mounted or embedded. Such modeling has been found useful for beams, plates and shell-like structures.[67] [68]

If there is concern about the ability of the actuator to transfer the strain through a bonding layer, a shear lag analysis of the bonding layer can be performed. The principle result of this analysis is the identification of the shear lag parameter, which must be kept small to allow for efficient transfer of strain to the host structure. The most general model is one which includes local shearing of the host structure.[69] Fortunately, Saint Venant's principle makes such a detailed model unnecessary for predicting the overall deformation of strain actuated structures. However, such an analysis is necessary for accurately predicting the strain field near and around active elements. Once the constitutive relations of the actuator, the assumed local strain deformation field, and the imposition of equilibrium are found, the influence of the strain actuator on the host structure can be calculated. Such models had been derived for embedded actuators as well as actuators in plates and shells.

The simple uniform strain model produces a useful figure of merit for comparing the effectiveness of various actuation materials. This model predicts that the strain induced in the host structure is proportional to the product of the actuation strain, which can be commanded in the actuation material, and the reciprocal of one plus the stiffness ratio (stiffness of the structure to that of the actuator). This latter term is an impedance matching effect which simply indicates that the stiffness of the actuator must be comparable to the stiffness of the structure for effective strain transfer.

3.1.2 Comparison of Commercially Available Strain Actuators

Commercially available strain actuating materials are listed in Table 2. There are four broad classes of materials which can create actuation strains. The first two columns represent two material classes (a piezoceramic and a polymer film) which use the piezoelectric effect. Piezoelectricity can be thought of as an interaction of the electrical field imposed upon the material with electrical monopoles in the material

[67] Crawley, E.F., "Intelligent Structures," SDM Lecture, Presented at the 33rd Structures, Structural Dynamics and Materials Conference, Dallas, TX, April 1992.

[68] Crawley, E.F. and de Luis, J., "Use of Piezoelectric Actuators as Elements of Intelligent Structures," AIAA Journal, Volume 25, Number 10, October 1987, pages 1373-1385.

[69] Pan, J., Hansen, C.H. and Synder, S.D., "A Study of the Response of a Simply Supported Beam to Excitation by a Piezoelectric Actuator," J. of Intelligent Material Systems and Structures, Volume 3, pages 3-16, January 1992.

Table 2: Comparison of actuation strain materials

	PZT G-1195	PVDF	PMN	TERFENOL DZ	NITINOL
Actuation Mechanicism	piezoceramic	piezo film	electrostrictor	magnetostrictor	shape alloy
Λ_{max}, μstrain	1,000	700	1,000	2,000	20,000
E, Msi	9	0.3	17	7	4(m), 13(a)
ε_{max}, μstrain*	350	10	500	580	8,500(a)
bandwidth	high	high	high	moderate	low

* for a sheet of actuator bonded to aluminum beam (ts/ta=10) in bending assuming AC value of Λ

(m) = martensite, (a)=austenite

itself. When an electric field is applied, the monopoles are pulled in the appropriate direction, straining the material and creating a strain in the direction of the field. This fundamental relation of piezoelectricity between field and strain is linear to first order.[70] The third column represents a material which creates actuation strain through electrostriction, which can be thought of as an interaction between the electric field and electric dipoles in the material which is inherently non-linear.[71] The fourth column is a magnetostrictor, which represents a coupling between an applied magnetic field and magnetic dipoles in the material and is also inherently non-linear. The absence of magnetic monopoles explains the absence of the fourth effect, which would be the interaction between magnetic fields and magnetic monopoles in the material. Shape memory is a qualitatively different effect, in which the application of electrical current causes heating in the material, and associated with the heating is a phase change, and strain. In some materials the strain associated with phase changes can be recovered when the material cools, which is called the shape memory effect.[72] [73]

All four of the material classes listed fulfill the basic strain actuator requirement of converting electrical inputs to strain in the material. A PZT is a common lead

[70] Cross, E.L., "Polarization Controlled Ferroelectric High Strain Actuators," J. of Intelligent Material Systems and Structures, Volume 2, July 1991, pages 241-260.

[71] Blackwood, G.H., Ealey, M.A., "Characterization of Electrostrictive Behavior in Lead Magnesium Niobate (PMN) Actuators at Low Temperatures" to appear in Ferroelectrics, January 1993.

[72] Baz, A., Iman, K. and McCoy, J., "The Dynamics of Helical Shape Memory Actuators," J. of Intelligent Material Systems and Structures, Volume 1, Number 1, January 1990.

[73] Liang, D., Rogers, C.A., "One-Dimensional Thermomechanical Constitutive Relations for Shape Memory Materials," J. of Intelligent Material Systems and Structures, Volume 1, Number 2, pages 207-234, April 1990.

zirconate titanate piezoceramic material having a maximum actuation strain on the order of 1,000 micro strain. PVDF is a polymer piezoelectric film which can produce about 700 microstrain, and PMN is a lead based electrostrictor which can create about a 1,000 micro strain. Terfenol, a rare earth magnetic-like material, can create about 2,000 microstrain at its non-linear maximum. And, nitinol (a nickel titanium alloy) can create up to 20,000 microstrain or 2% strain.

The modulus of each material, as seen in Table 2, is comparable to that of structural materials with the exception of the vinyl film, which has a significantly lower modulus. The next row in the table indicates the approximate strain which can be induced on the surface of an aluminum beam whose thickness is 10 times the thickness of the actuation material. This value indicates the range of strain which can be created in the host structure and is on the order of 3 to 500 micro strain with commercially available piezoelectric, electrostrictive, and magnetostrictive materials. In contrast, as much as .8% strain can be induced by the nitinol. However, the bandwidth of the nitinol is much lower than the other strain actuators, because of the necessity to introduce heat into the material and especially because of the time constants associated with the removal of heat to allow cooling. The trade-off which must therefore be made is one of strain authority versus bandwidth. The piezoelectrics and electrostrictives have quite high bandwidths, effectively beyond the frequency range of structural and acoustic control applications. Terfenol has a moderate bandwidth because of the difficulty in creating a rapidly changing magnetic field to influence the magneto-restrictive effectiveness.

3.2 Sensory Elements

Sensory elements of smart structures must be capable of being highly distributed and sensing the mechanical states of the structure. The ideal sensor for a smart structure converts strain or displacement (or their temporal derivatives) directly into electrical outputs. The primary functional requirements for such sensors are their sensitivity to the strain or displacement or their derivatives, spatial resolution, and bandwidth. Secondary requirements, which again might have to be traded in order to reach primary requirements, include the transverse sensitivity, the temperature sensitivity, linearity and hysteresis, electromagnetic compatibility, and size of sensor packaging. Unlike actuators, which are generally acknowledged to be sufficiently large and bulky so that they have to be explicitly accommodated for in the built up laminates, it is desirable to make sensors sufficiently small so that they can fit into intralaminar or otherwise unobtrusive positions.

3.2.1 Sensing Mechanisms

There are two types of sensors which can be used in smart structures, since they do not require a local reference point. These are acceleration and strain sensors. Acceleration, of course, is measured against an inertial reference frame. Current technology allows the acquisition of integrated circuit chip-based accelerometers. These

have been fabricated using silicon cantilever structures with piezoelectric capacitive, and electron tunneling detection mechanisms. Accelerometers are packaged in a way which allows them to be embedded into a structure or highly distributed over its surface. The output of the acceleration can be integrated once or twice in a high bypass manner to provide an inertial velocity or displacement at the point of measurements. Accelerometers are capable of making measurements over wide frequency ranges, including nearly quasi-static.

The alternative sensing scheme is to measure the strain in the structure (or the deflection of one point relative to another). Strain can be sensed at a point in the structure or averaged over a larger finite area in order to yield some particularly desirable output with the assistance of a weighting function.[74] [75] [76] Weighting functions can be chosen such that the output has frequency transfer function characteristics which are more desirable and unobtainable from temporal filtering of discrete point signals. The phase and amplitude characteristics of weighted discrete point signals are intimately related through the Bode integral theorem. However, because an area averaging sensor can be thought of as a device which can sense incoming strain waves before they reach the center point of the sensor, the device can in fact appear to be noncausal and thus violate the causality assumptions of the Bode integral theorem. This allows distributed strain sensors to have highly desirable roll-off characteristics with none of the associated undesirable phase loss. Note that such weighting functions can be applied to the output of any sensing device, including fiber optic sensors, and does not rely on a shaped piezoelectric strain gauge sensor.

3.2.2 Weighting Functions

Two commonly used weightings methods are modal sensors and discrete shaped sensors.[77] Modal sensors use sensitivity weighting functions which are distributed in such a way as to mimic the strain pattern in one of the structural modes. Therefore, modal sensor may be very sensitive to one mode, and through orthagonality, be relatively insensitive to other modes. The frequency domain output is therefore concentrated in bandwidths associated with particular modes of the system.

An alternative to modal sensing is discrete shaped sensing, in which sensors covers a finite section of the structure.[78] By using relatively simple weighting functions, such as triangular weighting or the Bartlett Window, discrete sensors can be made to roll-

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[74]Newnham, R.E., Safari, A., Giniewicz, J., Fox, B.H., "Composite Piezoelectric Sensors," Ferroelectrics, Volume 60, pages 15-21, 1984.

[75]Miller, D.W., Collins, S.A., Peltzman, S.P., "Development of Spatially Convolving Sensors for Structural Control Applications" Proceedings of the AIAA/ASME/ASCE/AHS 31st Structures, Structural Dynamics, and Materials Conference, Long Beach, CA, April 2-4, 1990, pages 1899-1906.

[76]Burke, S.E., Hubbard, J.E., Jr., "Spatial Filtering Concepts in Distributed Parameter Control," J. of Dynamic Systems, Measurement, and Control, Volume 112, pages 565-573, December 1990.

[77]Lee, C.K., Moon, F.C., "Modal Sensors/Actuators," J. of Applied Mechanics, Volume 57, pages 434-441, June 1990.

[78]Anderson, M.S. and Crawley, E.F., "Discrete Shaped Strain Sensors for Intelligent Structures," AIAA Paper 92-2406, Presented at the 33rd SDM Conference, Dallas, TX, April 1992.

Table 3: Comparison of strain sensors

	foil[a]	semiconductor[a]	fiber[b]	piezo film[c]	piezoceramic[c]
sensitivity	30 $\frac{V}{\epsilon}$	1000 $\frac{V}{\epsilon}$	$10^6 \frac{o}{\epsilon}$	$10^4 \frac{V}{\epsilon}$	$2x10^4 \frac{V}{\epsilon}$
localization, in	0.008	0.03	~0.04	< 0.04	< 0.04
bandwidth	DC - acoustic	DC - acoustic	~DC - acoustic	~0.1 Hz - GHz	~0.1 Hz - GHz

a) 10 V excitation
b) 0.04 in interferometer gauge length
c) 0.001 in sensor thickness

off rapidly in frequency, effectively acting as a low pass filter.

3.2.3 Commercially Available Sensors

Current commercially available sensing devices are listed in Table 3. Available sensing devices, which can be embedded in host structures, include traditional foil gauges, semiconductor strain gauges, embedded fiber optics, piezoelectric films and piezoceramics. Foil and semiconductor gauges rely on a change in resistivity associated with strain for their fundamental operation. Piezoelectric and piezoceramic devices use the piezoelectric effect which constitutes the coupling between the strain field and the voltage observed at the leads of the device. Fiber optic strain gauges rely on interferemetric effects to cause the optical output of the fiber to change with the strain.[79] [80] The sensitivities, indicated in Table 3, range from approximately 30 volts per strain for the foil gauges, through 10^3 volts per strain for the semiconductors, to 10^4 volts per strain for the piezoelectric and piezoceramic gauges. Fiber optics have a fundamentally different relationship between the output and measurement which is expressed in degrees per strain (fiber optics produce roughly 10^6 degrees per strain). The bandwidths of almost all the devices extend over the range of conventional structural control.

Considering that commercially available strain gauges are comparable in terms of their primary functional requirements of sensitivity, localization, and bandwidth, the choice of which to use in smart structures must be based on the secondary con-

[79]Sirkis, James S., Haslach, H.W. Jr., "Complete Phase-Strain Model for Structurally Embedded Interferometric Optical Fiber Sensors," J. of Intelligent Material Systems and Structures, Volume 2, pages 3-24, January 1991.

[80]Turner, R.D., Valis, T., Hogg, W.D., and Measures, R.M., "Fiber-Optic Strain Sensors for Smart Structures," J. of Intelligent Material Systems and Structures, Volume 1, April, 1990, pages157-174.

siderations. These considerations includes embeddability (which eliminates the soft piezoelectric films), the ability to introduce weighting functions, and electromagnetic compatibility issues (which generally reduces the attractiveness of foil gauges). In the associated electronics which must be incorporated in order to extract the strain signals, the last consideration tends to prejudice against the fiber optics. The remaining preferable strain sensors are therefore likely to be derivatives of the semiconductor based or piezoceramic devices, unless the signal conditioning electronics associated with embedded optics can be made small enough to accommodate wide spread distribution throughout a structure. Note that the sensitivities listed in Table 3 are made for reasonable excitation voltage, gauge length, and sensor thickness assumptions needed to place the various strain sensors into a common format.

With certain types of actuators and sensors another level of synthesis can be achieved, in which the same device can be used for both actuation and sensing.[81] Shape memory alloy fibers have been used in this application, as have piezoelectrics. In the case of piezoelectrics, the embedded material is modeled by combining the actuator and sensor constitutive relations. In this configuration, the piezoelectric can be considered a generalized transformer between the structural states (stress and strain) and the electrical states (charge and voltage).[82] By making use of the properties of a generalized transformers, the same device can be used as both an actuator and sensor through a technique referred to as simultaneous actuation and sensing, or sensuation.[83] [84] Typical sensuating circuits compare the charge which appears across a reference capacitor with the charge which appears across the piezoelectric. Nominally, the difference corresponds to the strain in the piezoelectric. Signal conditioning circuits can be designed to return either the strain or the strain rate as an output signal. This scheme operates essentially by using a mechanical capacitor as an estimator to estimate part of the electrical states. Sensuation is advantageous for active control application since the actuator and sensor are a perfectly collocated pair.

3.3 Control Methodologies and Algorithms

There are three levels of control methodology and algorithm design which must be considered for smart structures. These three levels are local control, global algorithmic control and higher cognitive functions. The objectives of local control are to add

[81]Hagood, N.W., von Flotow, A., "Damping of Structural Vibrations with Piezoelectric Materials and Passive Electrical Networks," J. of Sound and Vibration, 1991, 146 (2), 243-268.

[82]Hagood, N.W., Chung, W.H., von Flotow, A., "Modeling of Piezoelectric Actuator Dynamics for Active Structural Control," J. of Intelligent Material Systems and Structures, Volume 1, July 1990, pages 327-354.

[83]Dosch, J.J., Inman, D.J., Garcia, E., "A Self-Sensing Piezoelectric Actuator for Collocated Control," J. of Intelligent Material Systems and Structures, Volume 3 Number 1, pages 166-185, January 1992.

[84]Anderson, E.H., Hagood, N.W. and Goodliffe, J.M., "Self-Sensing Piezoelectric Actuation: Analysis and Application to Controlled Structures" AIAA Paper Number 92-2645, Presented at the 33rd AIAA Structures, Structural Dynamics, and Materials Conference Dallas, TX, April 1992.

damping and/or absorb energy and minimize residual displacements. The objectives of global algorithmic control are to stabilize the structure, control shapes, and reject disturbances. And in the future, controllers with higher cognitive functions will have objectives such as system identification, identification and diagnosis of component failures, the ability to reconfigure and adapt after failures, and, eventually, to learn.[85]

3.3.1 Optimal Local (Low-Authority) Control

In the design of local or low authority control, the principal issue is how to design the best controller, considering that hundreds or thousands of actuators and sensors may be distributed throughout the structure.[86] Further, it may be desirable to use local connections to introduce some level of control (or add some damping) into the structure before attempting to close global feedback loops with large numbers of actuators and sensors. Here the choice of ideal local control is quite obvious. Perfect local control is accomplished by simulating conditions of matched determination so that all of the impinging energy is absorbed by the controller.[87] However, simulating conditions of matched termination requires actuation and sensing of all independent cross sectional variables, which is usually not feasible in a structural controller. For example, in the case of a flexural wave such matched termination would require sensing of displacement and rotation, and actuating of moment and sheer at a point.

For the case of a system with a single output, the optimal compensator is found by matching the impedance of the compensator to the reciprocal of the complex conjugate of the dereverberated frequency transfer function.[88] [89] The dereverberated transfer function of a structure at the observation point is obtained by ignoring the effects of reflections from discontinuities in the boundaries in the far field. This can be obtained by smoothing or averaging the normally calculated frequency transfer function of the structure. In a limited number of cases, such dereverberated transfer functions can also be calculated from wave propagation theory.

Unfortunately, the optimal single-input single-output compensator is unachievable because the resulting transfer function is usually non-causal. Therefore, it is necessary to use the best causal approximation. Approximations can match the amplitude and/or phase of the non-causal compensator over some specified frequency range, but not over the entire frequency range of interest. The exact procedure is to determine the transfer function from actuator to sensor, dereverberate the transfer function, and

[85]Takagi, T., "A Concept of Intelligent Materials," J. of Intelligent Material Systems and Structures, Volume 1, pages 149-156, April 1990.

[86]Aubrun, J.N., "Theory of the Control of Structures by Low-Authority Controllers," J. Guidance and Control, Volume 3 Number 5, pages 444-451, Sept.-Oct 1980.

[87]Miller, D.W., Hall, S.R., von Flotow, A.H., "Optimal Control of Power Flow at Structural Junctions," J. of Sound and Vibration, 140 (3), pages 475-497, 1990.

[88]MacMartin, D.G., Hall, S.R., "Control of Uncertain Structures Using an H∞ Power Flow Approach," J. of Guidance, Volume 14, Number 3, May-June 1991, pages 521-530.

[89]MacMartin, D.G., Miller, D.W., Hall, S.R., "Structural Control Using Active Broadband Impedance Matching," Conference on Recent Advances in Active Control of Sound and Vibration, Virginia Polytechnical Institute and State University, Blacksburg, VA, April 1991.

approximate the dereverberated function with a causal approximation.

3.3.2 Optimal Global (High-Authority) Control

While local control is useful for adding damping and low-authority control, global or high-authority control must be utilized for objectives such as disturbance rejection, shape control, and stabilization of the structure. In the design of global controllers, one issue is how to establish a control architecture for structures with a large number of actuators and sensors. There are two limiting cases. The first is a completely centralized controller in which the signals from all the sensors are fed through the structure to a centralized processor. The control inputs are then computed and fed back throughout the entire structure to the distributed actuators. The second is a completely decentralized design, which is essentially the same as the local control already discussed. The centralized design would have the best performance, but would be computationally inefficient. A single centralized processor would have to process signals at rates corresponding to the highest mode being controlled, and would have to read all of the inputs and calculate all of the outputs for the entire system. Obviously, such huge computational requirements (typically on the order of 100x100 to 1,000x1,000 at speeds of 1,000 Hz) cannot be met, even with dedicated real time control computers (capable of computations on the order of 10x10 to 30x30 at roughly a 1,000 Hz).

3.3.3 Multi-Level and Select Feedback Path Methods

As a secondary consideration, the centralized scheme requires the passage of many relatively low level electrical signals, all the way from the original sensor to the centralized processing area. Thus the centralized scheme lacks both computational efficiency and consistently high signal-to-noise ratios. On the other hand, the decentralized scheme lacks good performance. And, although localized control can be used to add damping and reduce residuals, it cannot, in general, produce the type of performance achievable when information is fed back to actuators all over the structure. Therefore a compromise must be made between the two approaches. One approach proposed to address this problem is to use a scheme, midway between a completely centralized and completely decentralized control, which is referred to as a hierarchic or multilevel control architecture.[90] [91] In this scheme there would be two levels of control, a centralized controller for overall performance and distributed processing for local control. Such a structure would be divided into finite control elements with local processors providing local control using measurements made within the element and actuators within the element. An average representation of the shape within each

[90]Hall, S.R., Crawley, E.F., How, J.P., Ward, B., "Hierarchic Control Architecture for Intelligent Structures," J. of Guidance, Control, and Dynamics, Volume 14, Number 3, pages 503-512, May-June 1991.

[91]How, J.P., Hall, S.R., "Local Control Design Methodologies for a Hierarchic Control Architecture," Presented at the Guidance, Navigation and Control Conference, New Orleans, August 12-14, 1991.

element would then be passed on to the global processor for providing global high-authority control. This division of the control function into local and global control has been found to be quite practical, and from an engineering perspective completely reproduces the performance of a truly centralized structural controller.

Another form of control algorithm synthesis is the appropriate selection of actuator and sensors to simplify the structural control problem. Here the goal is to select some sensor/actuator pairing that simplifies the feedback form of a structural controller. In choosing a control scheme for a structure, one can in principle, select any form of actuator (applied force, applied moment, or applied distributed strain) and any form of sensor (displacement, displacement rate, or acceleration; slope, slope rate, or acceleration; or strain, strain rate, or strain acceleration). It may be that there is a desirable combination of these nine possible sensor outputs and three possible generalized force inputs which simplifies the structural control problem.

Several of these actuator and sensor selection issues have been investigated. For example, the control of the tip displacement of a cantilever beam was examined by applying a discrete moment actuator at 1/10 the length of the beam away from the root. The beam was modeled by assumed displacement finite elements and it was assumed that all of the displacement and rotations at the nodes were available as sensor outputs. Linear quadratic regulator theory was then applied, and the feedback from the nodal displacements and rotations to the discrete moment actuator was computed. By making use of the assumed displacement functions within the element, the continuous spatially distributed feedback gain function, from displacement and displacement rate output to the actuator input, was calculated. The function showed no regular or understandable pattern of displacement feedback. However, when the displacement feedback function is twice integrated to produce the equivalent strain feedback function, a much more regular and understandable pattern appears, implying that simpler output functions can be found for strain feedback than for displacement feedback.

In a more extreme and simplified example, the optimal output feedback was calculated for the control of sinusoidal flexural modes by distributed moment actuators. In this case, it was found that if transverse inertial velocity and strain were measured, the optimal output feedback for flexural waves of a uniform structure, assuming uniform weighting functions of the error, were exactly collocated. In other words, the optimal controller was found using collocated transverse velocity and collocated strain feedback to a collocated distributed moment actuator. This implies that in some cases local control is optimal even when considering a global actuator and sensor distribution.

3.4 Controller Architecture and Implementation Hardware

The presence of actuators and sensors and highly distributed control functionality throughout the structure implies that there must be a distributed computing architecture. The functional requirements for such a computing architecture include a bus architecture, an interconnection scheme, and a distributed processing arrangement.

The bus architecture should be chosen to yield a high transmission rate of data in convenient, probably digital, form throughout the structure. The interconnections must be suitable for connecting a (potentially) large number of devices, actuators, sensors, and processors with the least degradation of structural integrity. If the actuators and sensors are embedded within the structure, the interconnections also should be embedded within the structure in order to avoid the necessity of running the electrical connections through otherwise structurally important plies. Finally, the processing requires that the functionality, which includes signal conditioning, amplification, D/A and A/D conversion, and digital computation be distributed throughout the structure. Secondary requirements include minimizing electrical magnetic interference, maintaining the mechanical strength and longevity of the structure and of the electronics components, and thermal and chemical compatibility of electronic components within the host structure.

3.4.1 Bus Architecture

Selection of the bus architecture will strongly reflect the hierarchic control architecture chosen. Typically, structures will have distributed actuators and sensors which report (probably analog signals) to a local processor where the local control is calculated. These local processors then communicate over (probably digital) busses to the global processor. Trade studies have shown that distribution and embedding of a digital bus interface can simplify the overall interconnections in systems with more than 20 or 30 sensors and/or actuators.[92] Thus a relatively small number of actuators and sensors move the design toward one of a bus architecture.

3.4.2 Processing Hardware and Material Integration

The next natural question which arises is: are there embeddable processors which can perform the functions of the local controller? Here we only have to look at commercially available single-chip microprocessors, such as the Intel 87 C 196KB. This processor has a central processing unit, A/D, D/A, sample and hold functions, multiplexors, a serial port, high speed digital input/output, and 16K of memory on a single chip. This commercially available device operates at 12 MHz and integrates nearly all of the electronic functionality required to implement local processing for a hierarchic controller. With 16 bit precision, 10 inputs and 10 outputs, this device can perform the calculations for an LQR controller at 3 KHz. Alternatively, for a ten-state LQG controller, it can perform these calculations at 1,000 Hz. Thus the capabilities needed for the local processors are clearly achievable within the state-of-the-art.

The last question which must be answered is: can such micro-devices be embedded within a structural laminate? Here the issues which must be addressed are whether the device will survive the temperature and pressure cycles of the curing process, and

[92] Warkentin, D.J., Crawley, E.F., "Prospects for Electronic Component Distribution in Intelligent Structures," Presented at the ADPA/ AIAA/ ASME/SPIE/ Conference on Active Materials and Adaptive Structures, November 1991, Alexandria, VA.

whether they can survive the periodically applied strain fields of the operational environment as well as the temperature and humidity conditions of general operation. A preliminary investigation of this subject has been completed which finds that the embedding of micro-devices is feasible within common structural laminates.[93] Electronic devices, without protective packaging, have been embedded and cured in laminated test coupons. These coupons were subjected to quasi-static loads, and the first ply failure occurred at nearly 8,500 microstrain and subsequent ply damage was recorded up to nearly 13,000 microstrain. The electronic device continued to function normally all the way to failure of the test coupon. In addition, embedded, but chemically, electrically and mechanically isolated, integrated circuits have been shown to function up to the breaking point of typical graphite epoxy laminates. The remaining challenge in this area is to increase the robustness of the device's electrical contacts, which are subject to fatigue loading and long-term temperature, humidity, and hermicity disturbances.

3.5 Signal Conditioning and Power Amplification

Most of the issues relevant to signal conditioning and power amplification have been discussed in the previous sections. The most important of these issues are architecture configuration and embeddability. However, application of these technologies requires that heat dissipation and structural integrity issues be addressed. These issues must be considered since signal conditioning and power amplification circuitry often are large and generate considerable heat.

Some of the signal processing requirements can be alleviated by using distributed actuating and sensing techniques to spatially process signals in hardware or by taking advantage of local controllers.

On the other hand, power amplification for smart structures is a difficult problem because of the considerable bulk and heat dissipated by these devices. Miniaturization techniques promise to alleviate these problems, and are being pursued vigorously. However, embeddable amplifying equipment is not yet commercially available. An alternate and innovative solution to embedding amplifiers is the use of high power signal switching. These techniques make use of graduated power lines and high speed switching between lines to avoid embedding amplifying devices. Unfortunately, such techniques are only in the preliminary development stages.

[93]Warkentin, D.J.., Crawley, E.F.., Senturia, S.D., "The Feasibility of Embedded Electronics for Intelligent Structures," AIAA paper Number 91-1084, Journal of Intelligent Material Systems and Structures, Volume 3, pages 462-482, July 1992.

3.6 Some Previous Applications for Controlled Structures

A wide variety of applications exist for smart structures technologies.[94] These include aeroelastic control and maneuver enhancement,[95] reduction of vibrations and structure borne noise,[96] [97] load alleviation in structures, jitter reduction in precision pointing systems,[98] shape control of plates,[99] [100] trusses and lifting surfaces, and isolation of offending machinery and sensitive instruments.

Despite the fact that truly smart structures have not yet been built, a number of experimental implementations of smart structures component technologies have been built and demonstrated. In particular, many researchers have investigated applications of distributed actuators and sensors and advance control algorithms. What is lacking to date is the distribution of the control and processing, but these parts of the technology are expected to evolve in time. Four examples found in the recent literature are discussed below. These examples are the aeroservoelastic control of a lifting surface, precision control of a truss, seismic and control of a building, and control of radiated sound.

In the first example, a typical high performance aircraft-like wing was built out of a graphite epoxy laminate with piezoelectric actuators distributed over 71% of its surfaces.[101] The actuators were arranged into three banks which consisted of the vertical columns shown in Figure 2. The actuators were wired so as to induce bending in the laminate. Three tip displacements were used for displacement feedback. The controller implemented was a reduced order, 14-state LQG controller. The control objective was gust disturbance rejection and flutter suppression.

Shown in Figure 3 are the analytically predicted and experimentally measured open and closed loop control. As can be seen, the DC response of the structure was reduced by almost 10 db, which corresponds to approximately a factor of three stiffening in the structure due to the application of the closed-loop control. The

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[94]Pan, Hansen, and Synder, *op. cit.*

[95]Lazarus, K.B., Crawley, E.F. and Lin, C.Y., "Fundamental Mechanisms of Aeroelastic Control with Control Surface and Strain Actuation," Proceedings of the 33rd SDM Conference, Baltimore, MD, April 1991, pages 1817-1831.

[96]Miller, D.W., Hall, S.R., "Experimental Results Using Active Control of Traveling Wave Power Flow," J. of Guidance, Control, and Dynamics, Volume 14, Number 2, pages 350-349, March-April 1991.

[97]Fuller, C.R., Gibbs, G.P., Silcox, R.J., "Simultaneous Active Control of Flexural and Extensional Waves in Beams," J. of Intelligent Material Systems and Structures, Volume 1, pages 235-247, April 1990.

[98]Fanson, J.L., Blackwood, G.H. and Chu, C-C., "Active -Member Control of a Precision Structure," AIAA/ASME/ASCE/AHS 30th Structures, Dynamics, and Materials Conference, April 1989.

[99]Crawley, E.F., Lazarus, K.B., "Induced Strain Actuation of Isotropic and Anisotropic Plates," AIAA Journal, Volume 29, Number 6, pp. 944-951, June 1991.

[100]Kashiwase, T., Tabata, M., Tsuchiya, K., Akishita, Sadao, "Shape Control of Flexible Structures," J. of Intelligent Material Systems and Structures, Volume 2, pages 110-125, January 1991.

[101]Lazarus, K.B., Crawley, E.F., "Multivariable High-Authority Control of Plate-like Active Structures," AIAA Paper Number 92-2529, Presented at the 33rd AIAA Conference on Structures, Structural Dynamics, and Materials, Dallas, TX, April 1992.

- Piezoceramic actuators cover 71% of surface
- 3 Tip displacement sensors
- Reduced order LQG Control
- Gust disturbance rejection and flutter suppression

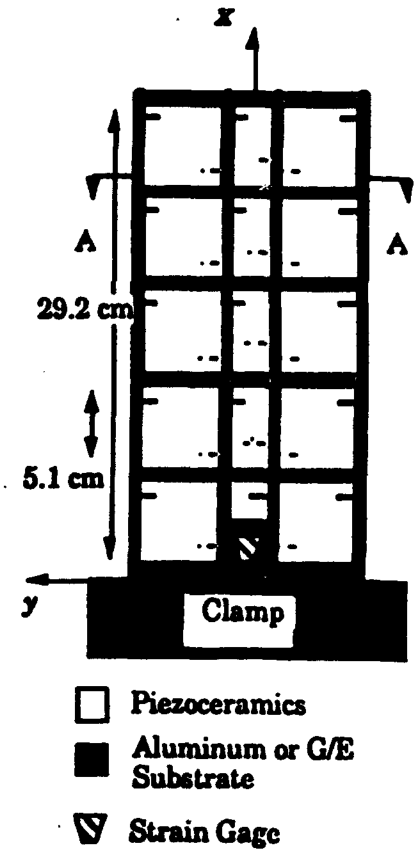
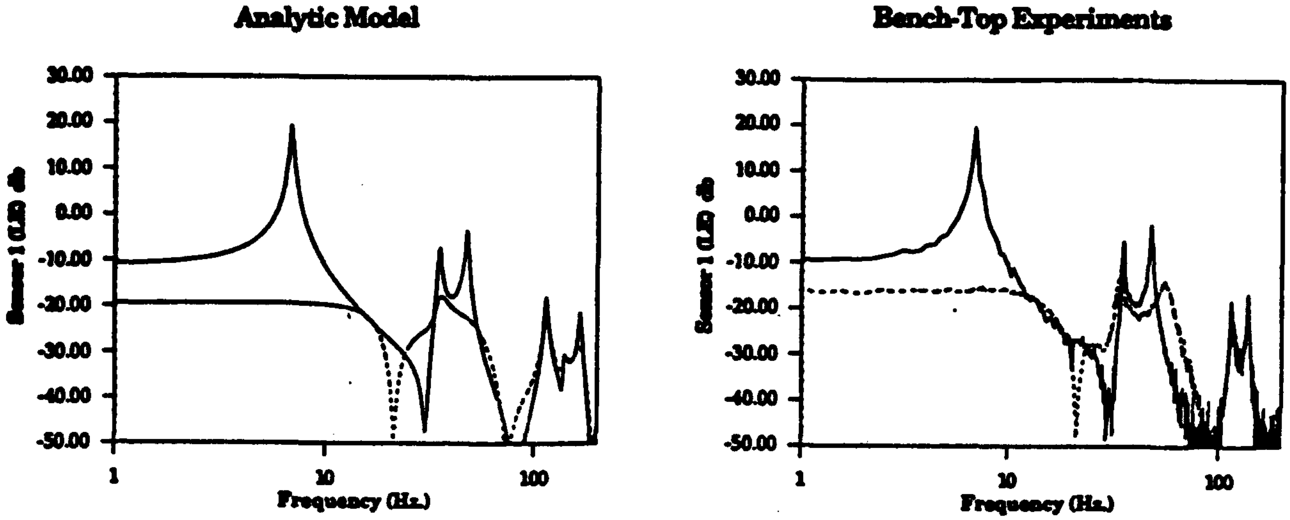


Figure 2: Aeroservoelastic control example

first mode was virtually eliminated from dynamic consideration, being reduced 30 db from an already present 1% damping. The second mode, which was torsional, was less strongly influenced, with a 10 db reduction. This was due to the fact that this mode was less controllable than the first or third mode. The third mode achieved a 20 db reduction. Overall, the RMS response in bandwidth up to 100 hertz was reduced by about 15.4 db. This is an example of the relatively high gain control which can be introduced into a structure, and is probably the largest control authority which has yet been reported on a structural test article in experimental implementation.

The second example of a prototypical smart structure is the "dial-a-strut" or locally controlled strut, which is part of a precision control truss experiment (see Figure 4).[102] In this case, the structure contains two active piezoelectric struts. Each strut has a collocated displacement and force feedback. By making measurements of the collocated displacement and force, the localized optimal impedance matching described earlier can be implemented. The control objective of this experiment was disturbance rejection of on board machinery noise, which would be typical of the need to reduce the jitter in a interferemetric spacecraft. Figure 5 shows typical transfer functions (open-loop and closed loop) for one and two of the dial-a-struts. By comparing the open-loop and two strut closed-loop response, it can be seen that the first and second structural modes were significantly modified. Both the first and

[102]Fanson, J.L., Chu, C., Lurie, B.J., Smith, R.S., "Damping and Structural Control of the JPL Phase 0 Testbed Structure," J. of Intelligent Material Systems and Structures, Volume 2, pages 281-300, July 1991.



- ~10 db reduction in steady state response
- Reduction in response of 30, 10, and 20 db in the first three modes
- RMS response reduction of 15.4 db

Figure 3: Analytical and experimental results of aeroservoelastic control example

second mode response was reduced by 40 db. Note, however, that in this cases the initial structural damping was quite low (roughly a few tenths of a percent). Thus the local collocated approximation to the optimal non-causal controller is seen to achieve good performance in a realistic structural configuration.

The seismic control of buildings is a considerably larger scale application of smart structures. Experiments were performed on model building with a simulated earthquake disturbance (see Figure 6).[103] Control was effected by an active shear brace incorporated into the structure. Five transverse accelerometers were used to monitor the control response of the structure, and two of them were used for feedback control. The control objective was to minimize building acceleration in response to a simulated disturbance, which simulated a typical large earthquake. Figure 7 shows the building excitation with and without the control system. As a result of the closed loop control, the damping factor was increased from nearly zero to twenty percent in the first three modes, with significant reduction in the low frequency component.

The final example considers the reduction of sound radiated into a room or aircraft cabin by active control of the plate and shell-like members which form the walls. To simulate this situation, a rectangular plate was placed inside a test chamber.[104] The

[103]Nishimura, I., Abdel-Ghaffar, A.M., Masri, S.F., Miller, R.K., Beck, J.L.., Caughey, T.K., Iwan, W.D., "An Experimental Study of the Active Control of a Building Model," J. of Intelligent Material Systems and Structures, Volume 3, Number 1, pages 134-165, January 1992.

[104]Clark, R.L. and Fuller, C.R., "Control of Sound Radiation with Adaptive Structures," J. of

- 2 Active piezoelectric struts
- Collocated displacement and force feedback
- Impedance matching control
- D' sturbance rejection (on-board machinery noise)

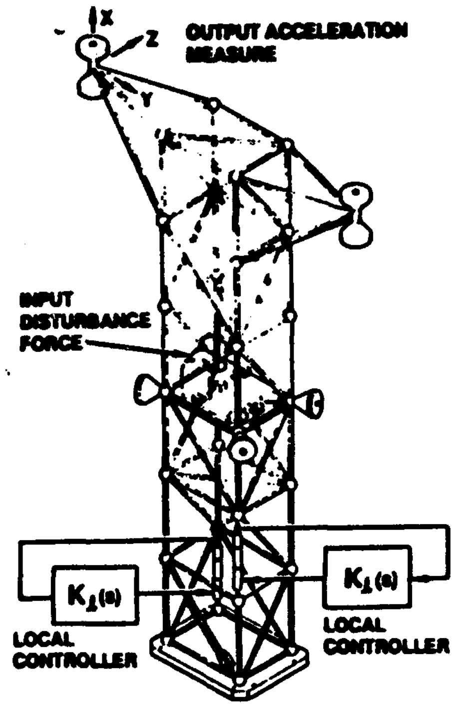
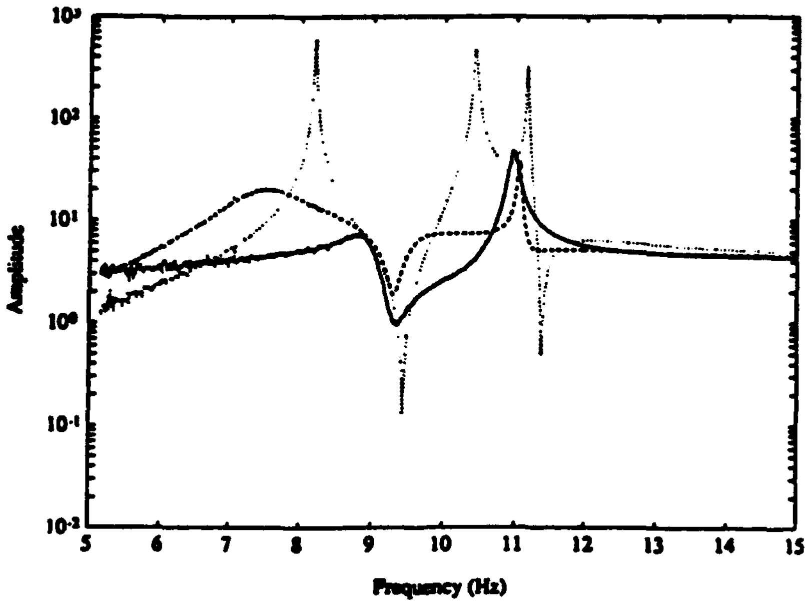


Figure 4: Precision truss control experiment



- Open loop (dotted) vs. closed loop for one (dashed) and two (solid) Dial-a-Struts

Figure 5: Results using one and two struts in precision truss control experiment

- 1 Active shear brace
- 5 Transverse accelerometers (two sensors needed for control)
- Minimax velocity transfer function
- Minimize building acceleration response to nonstationary base motion

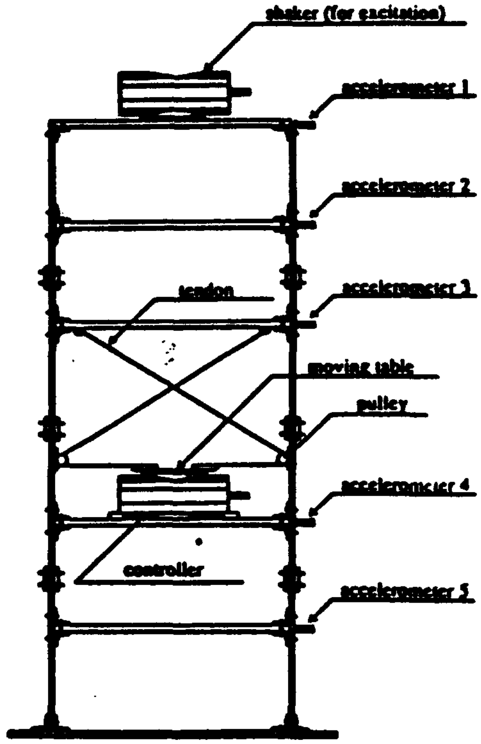
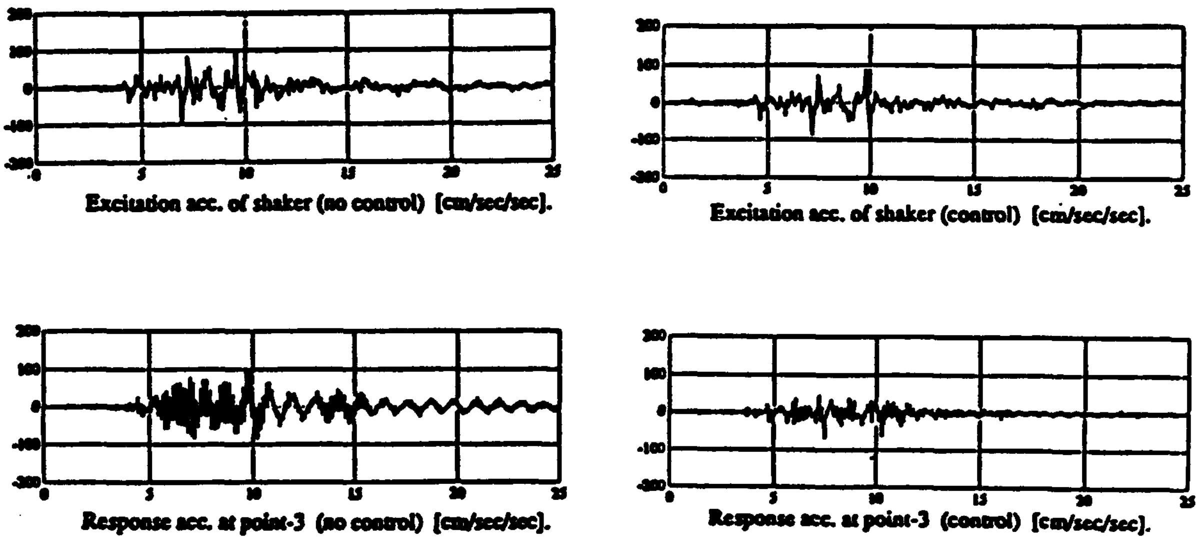


Figure 6: Experiment for seismic control of a building



Open-loop **Closed-loop**

- Damping factor increased from ~0% to 20% in first three modes
- Significant reduction in low frequency component

Figure 7: Results of seismic control experiment

- 3 Piezoceramic actuators
- 2 Piezoelectric film sensors
- Adaptive LMS (Least Mean Square) feed forward
- Narrow band noise radiation minimization in far field

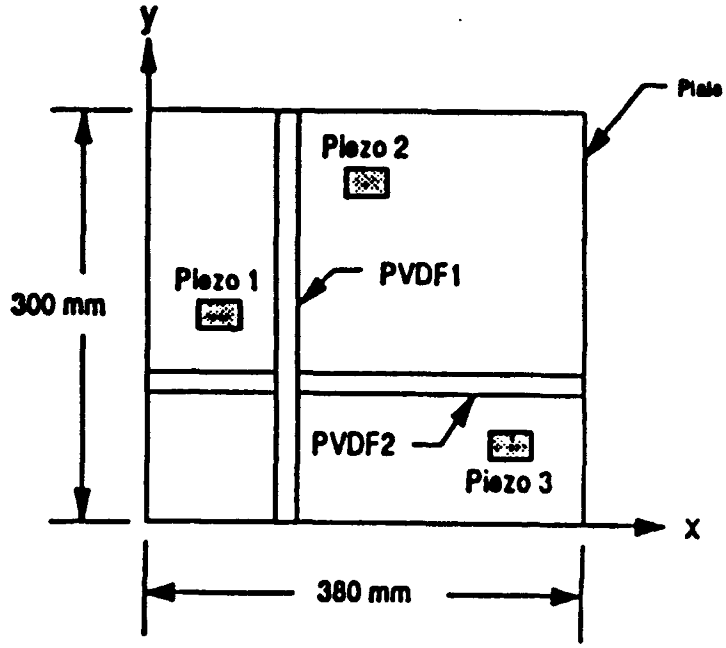


Figure 8: Experiment to control sound radiation

plate was controlled by three piezoceramic actuators placed as shown in Figure 8. Two PVDF piezoelectric film sensors were used to measure the vibration of the plate. The excitation source was an electromagnetic shaker which drove the plate at a known frequency corresponding to, for example, the excitation of an aircraft cabin wall from the rotation of the propeller outside the wall at a known RPM. In these cases, adaptive LMS algorithms are likely candidates for the control scheme. These schemes make use of knowledge of the frequency at which the primary excitation is occurring. The control objective in this example was narrow band reduction of the radiated far field noise. Figure 9 shows the radiated sound pressure level for the open-loop case, and the cases of one-piezoceramic actuator with one-sensor and two piezoelectric actuators with two sensors. As can be seen from the diagram on the left, the radiated sound pressure level was reduced by about 30 db. The figure on the right indicates that this was achieved by principally reducing the response of the three-one mode, which corresponded to the frequency of the excitation source.

These four examples are but a small number of the cases where investigators throughout the world are now applying distributed actuation and sensing to a wide variety of control problems. It is encouraging that these early experiments not only show the feasibility of smart structures application, but remarkably good agreement between theory and experimental results as well. Of course, further experimentation is necessary in order to establish the technological limitations as well as the feasibility

Intelligent Material Systems and Structures, Volume 2, July 1991, pages 431-452.

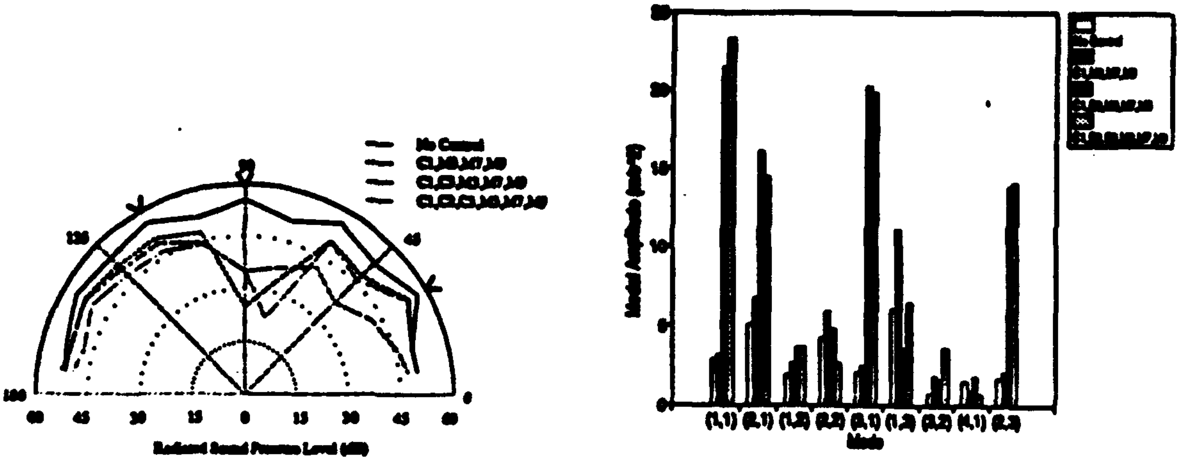


Figure 9: Results of experiment to control sound radiation

of distributing the processing and control architectures.

4. Neural Networks

Neural networks have recently received much attention in the research community. In Air Force applications alone, the use of neural networks has been explored for aircraft (friend or foe) recognition, target identification, guidance and navigation, mission configuration and shape control, damage detection, and structural vibration and acoustic radiation control. The popularity of neural networks stems from their promises of providing the capability to process huge amounts of data, quickly classify complex images, autonomously identify unknown systems, and control dynamic systems without a priori models. Neural networks are most popular in areas where current classification, identification and control methods are inadequate due to prohibitive data processing and modeling requirements.

This section examines the use of neural networks for a small subset of possible applications - the control of flexible structures. Again the desire for examining the use of neural networks for controlling flexible structures is motivated by the shortcomings of current methods. Problems with current structural control methods are the result of two deficiencies. The first is a lack of useful design and analysis techniques for systems other than those which are linear and time-invariant. The second is the difficulty of modeling or identifying complex systems even if they can be well represented by linear time- invariant models. These two issues are elaborated upon below.

4.1 Structural Control Limitations

Linear systems theory currently provides well established optimal control analysis techniques and design methodologies based on linear algebra, complex variable theory, and the theory of ordinary differential equations.[105] In contrast, techniques for non-linear or time varying systems are quite limited, requiring design and analysis methods to be established on a system-by-system basis. Consequently, methods that simultaneously design controllers for stability, robustness and performance are unavailable for all but a few simple non-linear time varying systems. Unfortunately, the problems associated with control law synthesis and closed loop performance are not limited by non-linearities and time varying parameters. Controller performance is also effected by analytical model fidelity as well as sensor accuracy, actuator performance, and controller hardware. Note that these factors are interrelated, since the structural dynamics modeled (including actuator and sensor dynamics) affects the size of the analytic model and the hardware required for implementation.

Difficulties in designing high-performance structural controllers have forced engineers to adopt a human-in-the-loop design approach. This technique requires extensive model refining and updating, and an iterative "trial and error" controller implementation process. Many man-hours of model and controller analysis and redesign are

[105]Narendra, K.S. and Parthasarathy, K., "Identification and Control of Dynamical Systems Using Neural Networks," IEEE Transactions on Neural Networks, Volume 1 Number 1, March 1990, pages 4-27.

required to converge on effective designs with the human-in-the-loop approach. While the results sometimes meet mission requirements, this iterative time consuming process becomes impractical and often impossible for systems with changing parameters and configurations (such as aircraft). Moreover, space-based applications completely eliminate any hope of success with human-in-the-loop, "trial and error" methods.

As a result of the problems described above, interest has increased in developing control methodologies for controlling structures which do not rely on either linear systems theory or accurate models. Techniques are desired which have the ability to autonomously synthesis control laws in situ and on-line. Neural networks may be able to offer such a capability, and it is the goal of this report to assess the potential of this methodology to control flexible structures. This assessment is made by first reviewing the components of neural network architectures and then reviewing the basic functionality of structural controllers. Following these reviews, some applications of neural controllers recently reported in the literature are examined and assessed. Finally, a strategic plan for the development of neural networks for structural control is provided.

4.2 Review of Neural Networks

Neural networks are information processing units which are composed of processing elements, weighting functions, and interconnections. The design of neural networks consists of two fundamental components. The first is choosing the physical architecture of the network and the second is selecting appropriate training and recall algorithms.

4.2.1 Architecture

The basic unit of a neural network is the processing element, which is often referred to as a neuron. All computation is done in the processing element. As shown in Figure 10, processing elements perform mathematical operations on a weighted sum of the inputs to produce some desired output. A threshold value θ is sometimes included in the processing element as shown below

$$y = F(x, W, \theta) \tag{8}$$

where x is the input vector, y is the output vector and W is weight. In neural networks, the weights are variable and adjusted by some training algorithm (discussed below), while the mathematical operations performed by the processing elements are fixed. Typically, each processing element takes a linear combinations of the input values and associated weights and then enters the result in a threshold function. Simpson[106] and Hecht-Nielson[107] detail networks which follow this format, which can

[106]Simpson, P., Artificial Neural Systems: Foundations, Paradigms, Applications and Implementations, Pergamon Press: Elmsford, NY, 1990.

[107]Hecht-Nielson, R., Neurocomputing, Addison-Wesley: Reading, MA, 1990.

be expressed mathematically by

$$y = f\left(\sum_{i=0}^{n} x_i W_{ij}\right) = f\left(X \bullet W_j\right) \tag{9}$$

where the function $f()$ is some chosen threshold function.[108] Threshold functions are used to map a processing element's (sometimes) large value onto a domain with a prescribed range. This prevents values calculated from summations of inputs and weights in one layer from saturating inputs to the next layer (network layers are depicted in Figure 10). Threshold functions are also the means by which non-linearities (if desired) are introduced into the network dynamics. There are many types of thresholds used in neural networks, including linear, step, ramp, sigmoid and Gaussian functions.[109] The most commonly used threshold function is the sigmoid.[110] This S-shaped function is a non-linear, continuous version of a step, and is described by

$$f(x) = \frac{1}{1 + e^{-\alpha x}} \tag{10}$$

where α is a value greater than zero and is usually set to unity.[111] A complete neural network is composed of processing elements and inter-connections which connect the processing elements to each other and to the outside world. The organization of these inter-connections is referred to as the topology or architecture of the network. Neural networks are organized into groups of processing elements called layers as shown in Figure 10. There are three types of layers: Input layers connect the inputs to the network to other network layers, output layers connect network layers to the outputs, and hidden layers connect network layers to other network layers. The architecture is completed by appropriately connecting layers of processing elements.

Neural network topologies are classified by the number of layers and how information flows between layers. When information flows only in the direction from the inputs to the outputs, the architecture is described as a feedforward network. Feedback or recurrent networks also have paths which allow information to flow in the opposite direction (from outputs to inputs). One could imagine the construction of very complex topologies with many layers, information flow directions, and types of processing elements, and research on a variety of different network types appears in the literature.[112] [113] [114] However, since any arbitrary non-linear function can be represented by a feedforward network with one hidden layer and some

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[108]Simpson, K.P., "Neural Network Paradigms," AGARD-LS-179, AGARD Lecture Series Number 179, Neubiberg, Germany, October 1991, pages 2.1-2.33.

[109]Simpson, *op. cit.*

[110]Kosko, B., Neural Networks and Fuzzy Systems: A Dynamic Systems Approach to Machine Intelligence, Prentice Hall, 1992.

[111]Douglas, J., "Neural Nets for Control, What Gives Them the Nerve?" SERC Report Number13-92R, Massachusetts Institute of Technology, Cambridge, MA, 1992.

[112]Narendra and Parthasarathy, *op. cit.*

[113]Simpson, *op. cit.*

[114]DeCruyenaere, J.P. and Hafez, H.M., "A Comparison Between Kalman Filters and Recurrent Neural Networks," IEEE 0-7803-0559-0/92, 1992.

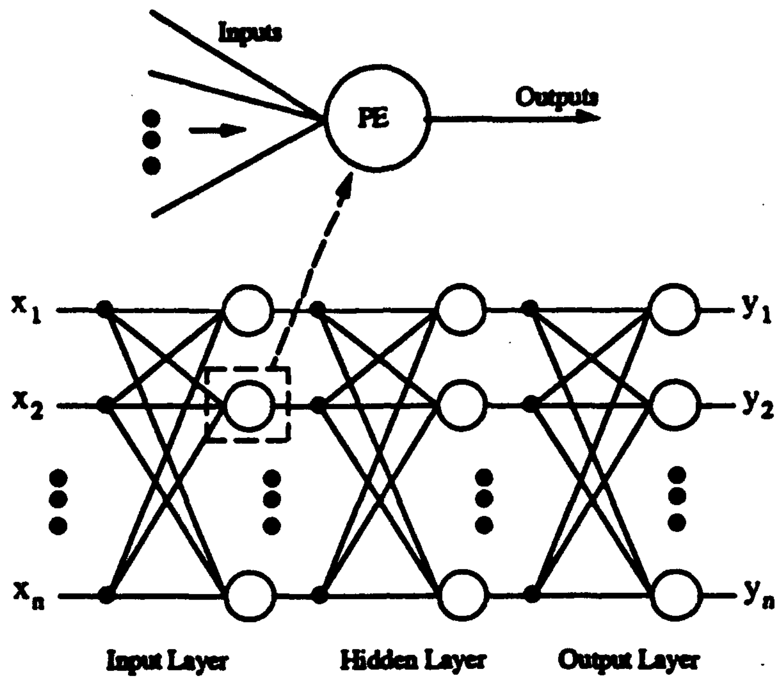

Figure 10: Three layer feedforward neural network with exploded view of a processing element (PE)

non-linear threshold function,[115] most researchers use only relatively simple networks. Further, most structural control investigations found in the literature use multilayer feedforward networks, however it is unclear whether or not this is the best choice for structural control.

4.2.2 Training and Recall

In addition to the many topology options, the neural network designer must choose between many available methods for training the network. Network training is the process by which the weights are set. The ability to set the weights of the network based on some training rule is what gives neural networks the capability to learn to perform functions without a priori knowledge and in situ. However, the need to learn also causes the functionality of the network to be dictated by (and sometimes limited by) the effectiveness of the training procedure. Network training techniques fall into two broad categories, supervised learning and unsupervised learning. Currently, supervised learning techniques show the most promise for control applications.

In supervised learning the "supervisor" chooses the type and duration of training. Most networks are trained using this type of learning. Supervised learning schemes

[115]Hornik, K., Stinchcombe, M. and White, H., "Multilayer Feedforward Networks are Universal Approximators," Neural Networks, Volume 2, Number 5, 1989, pages 359-366.

include error correction learning or backpropagation,[116] reinforcement learning[117] and stochastic learning.[118] An excellent review of these and other learning algorithms is presented in Simpson.[119]

For structural control applications backpropagation is the most widely employed supervised learning method.[120] This method chooses the network weights by minimizing an error or cost

$$E_k = \frac{1}{2}\sum_j (Z_{kj} - y_{kj})^2 \tag{11}$$

where y is the actual and z is the desired output of the j^{th} element for some set of data k. Ideally the error should be minimized for each set of data. But causality dictates that future errors are unknown, so the weights are adjusted based on the error found in each set of data. The weights at the output layer are calculated based on the error, which is then backpropagated toward the input layer to adjust the other network weights. Note that this method does not guarantee convergence to some optimal set of weights, but has proved to be quite effective at training neural networks for a variety of applications including structural control.

4.3 Controller Functions

Control systems may perform a variety of tasks in Air Force systems including aircraft recognition, target identification, guidance and navigation, damage detection and structural control. Each of these tasks requires controllers with several different elements or components. For example, target recognition necessitates elements for data processing, data filtering and pattern matching. In some cases a single processor can be used for all functions, however it is usually desirable to have each sub-task performed by algorithms and hardware optimized for that specific function. Table 4 shows the required controller functions for some typical Air Force control tasks.

As shown each task requires different combinations of functionality, which indicates that a controller capable of target recognition (processing, filtering and pattern matching) may not be capable of structural control (state estimation and gain selection). Thus the functional capabilities of a particular control methodology must be known in order to evaluate its usefulness in any particular application. These concepts must be considered in assessing the use of neural networks for structural control.

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[116] Barto, A., "Simulation Experiments with Goal-Seeking Adaptive Elements," Technical Report AFWAL-TR-84-1022, Air Force Wright Aeronautical Laboratory, 1984.

[117] Widrow, B. and Stearns, S., Adaptive Signal Processing, Prentice-Hall: Englewood Cliffs, NJ, 1986.

[118] Ackley, D., Hinton, G. and Sejnowski, T., "A Learning Algorithm for Boltzmann Machines," Cognitive Science, Volume 9, 1985, pages 147-169.

[119] Simpson, *op. cit.*

[120] Antsaklis, P., "Neural Networks in Control Systems," IEEE Control Systems Magazine, April 1992, pages 8-10.

Table 4: Controller tasks versus functionality

	Aircraft Recognition	Target ID	Guidance and Nav.	Damage Detection	Structural Control
Processing and Filtering	√	√	√	√	√
Pattern Machining	√	√		√	
Parameter Identification	√	√		√	√
State Estimation			√		√
Gain Selection			√		√
Adaption	?	?	?	√	√

4.4 Neural Net Applications for Control

A review of the literature shows that neural networks have demonstrated some of the functionality required for structural control. The function which has been demonstrated most convincingly to date is that of parameter or system identification. Neural networks have been used to identify a host of linear and non-linear dynamic systems. Excellent reviews of recent work in this area are presented by Narendra and Parthasarathy[121] and Qin, Su and McAvoy.[122]

In addition, recent work has shown that neural networks can perform the other functions needed for controlling dynamic systems (perform estimation and gain selection), at least for simple examples. Nguyen and Widrow[123] used multilayer feedforward networks, trained by backpropagation, to control a truck backing up. They found that a two step process was needed to train the network which had 45 units in the hidden layer. First, the network was trained to emulate the system dynamics (estimation). Then, it was trained to control the system (gain selection). This technique proved quite effective, however it took 20,000 sessions to train the network to control the relatively simple system. Good results also have been obtained using other types of networks and training algorithms such as global reinforcement learning.[124]

Although the ability to control dynamic systems (in general) is encouraging, it does not necessarily guarantee the ability to control flexible structures. This is because flexible structures have features which make control law synthesis difficult. These include lightly damped complex poles and infinite numbers of modes, which makes pole cancellation and plant inversion impossible. Unfortunately, there is no theory for analyzing the effects of these features on the performance of neural controllers.

[121] Narendra and Parthasarathy, *op. cit.*

[122] Qin, S.-Z., Su, H.-T. and McAvoy, T.J., "Comparison of Four Neural Net Learning Methods for Dynamic System Identification," IEEE Transactions on Neural Networks, Volume 3, Number 1, January 1992, pages 122-130.

[123] Nguyen, D. and Widrow, B., "The Truck Backer-Upper: An Example of Self-Learning in Neural Networks," Neural Networks for Control, The MIT Press, 1990.

[124] Barto, A., Sutton, R. and Anderson, C., "Neuronlike Adaptive Elements That Can Solve Difficult Learning Control Problems," IEEE Transactions on Systems, Man, and Cybernetics, Volume 13, Number 5, 1983, pages 834-846.

However several investigators have successfully used neural networks for controlling very simple flexible structures. Regelbrugge and Calalo[125] used a probabilistic neural network to identify the dynamics of a simple structure. Napolitano and Chen[126] showed that a multilayer feedforward network could estimate the first two modes of a cantilever beam. And, Helferty, Boussalis and Wang[127] used a multilayer feedforward network to control a three mode system. Thus, each of the required components (identification, estimation and gain selection) have been demonstrated for simple structures.

Despite the limited success demonstrated to date, very little is known theoretically about using neural networks for control. For instance, Bozich and MacKay[128] showed that an isolation table with a feedforward network was more proficient at rejecting narrowband disturbances than broadband excitations, but no explanation of the limiting mechanism was offered. Questions need to be addressed such as (1) are neural networks not capable of broadband control, (2) was the training algorithm inadequate or (3) should a different topology be used. Further, all of the structural controllers presented were demonstrated using simple examples and it is unclear how these results will scale to realistic structures in terms of increase in network size, training duration required, network convergence, and system stability. Considering the long training times demanded by the most successful methods (multilayer feedforward topology with backpropagation training), much work is needed before neural networks can be applied to complex structures with high performance requirements.

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[125] Regelbrugge, M.E. and Calalo, R., "Neural Network Applications in Structural Dynamics," Proceedings of the Conference on Active Materials and Adaptive Structures, Alexandria, VA, November 1991, pages 785-790.

[126] Napolitano, M.R. and Chen, C.I., "Application of a Neural Network to the Active Control of Structural Vibration," Proceedings of the Conference on Active Materials and Adaptive Structures, Alexandria, VA, November 1991, pages 247-252.

[127] Helferty, J.J., Boussalis, D. and Wang, S.J., "Distributed Control Concepts Using Neural Networks," Proceedings of the Conference on Active Materials and Adaptive Structures, Alexandria, VA, November 1991, pages 461-465.

[128] Bozich, D.J. and MacKay, H.B., "Neurocontrollers Applied to Real-Time Vibration Cancellation at Multiple Locations," Proceedings of the 2nd Joint Japan/U.S. Conference on Adaptive Structures, Nagoya, Japan, November 1991, pages 326-325.

5. Health Monitoring

All flexible aircraft and space structures are designed to meet stringent specifications and are therefore susceptible to damage during their operational life. Damage left undetected can cause structural deterioration and jeopardize mission success and crew safety, and this damage cannot be corrected unless some means for its detection is available. Therefore many methods of damage detection have been developed. However, currently available methods are costly, time consuming, subject to human error and sometimes ineffective. Poor damage detection schemes are usually exposed in dramatic fashion, as was the case in the Aloha Boeing 737 accident.[129]

Deficiencies in current damage detection techniques motivate the development of new methods. One possible way to improve methods for structural damage detection and health monitoring is through the use of smart material systems. Much research and development work has been done recently on smart material systems, especially in areas related to the use of smart materials as integrated components (actuators and sensors) of intelligent structures. It is hoped that these integrated actuators and sensors (particularly sensors) can be used to improve damage detection capabilities. Ideally, a structure would be able to monitor its own health with an internal nervous system of integrated sensors.

The first section below reviews some of the many health monitoring applications and the central problems associated with developing damage detection systems. The next section examines the fundamental technical issues involved in detecting damage and is followed by a discussion of some detection methods which utilize smart material systems. In this report aircraft structures are emphasized, however the concepts discussed apply to the damage detection of numerous systems with flexible structures.

5.1 Motivation for Damage Detection

Damage detection methods are motivated simply by the desire for the information necessary to make informed decisions about the health of a structure and any required maintenance or corrective measures.

5.1.1 Potential Applications

Such information is needed for in-flight structural monitoring as well as aircraft certification and load history recording.[130] These applications require large amounts of information to be sensed and processed, and have great potential for benefiting from intelligent structures with integrated sensors and distributed processing.

[129]Gerardi, T.G., "Health Monitoring Aircraft," J. of Intelligent Material Systems and Structures, Volumel, July 1990, pages 375-385.

[130]Horner, C.G., Chairperson, "A State-of-the-Art Assessment of Active Structures," NASA TM 107681, NASA Langley Research Center, Hampton, VA, September 1992.

Aircraft Certification

New aircraft must undergo testing to certify that the aircraft meets the desired strength, performance and handling qualities. This hazardous testing can be performed only by gradually increasing the limits of the flight envelope because actual limits are unknown. During testing, the structural health is monitored by a limited number of instruments which may not detect catastrophic damage since load distributions are estimated only by unverified models. The availability of on-line health monitoring would enable pilots to reduce loads when damage is detected and return safely. This would not only save the lives of test pilots, but would reduce the cost of testing by limiting damage to aircraft structures and the number of lost aircraft.

In-flight Structural Monitoring

Operational aircraft must be constantly checked to ensure structural integrity. This is due to the large number of factors which can cause structural damage even if the aircraft remains within the expected flight envelope. This constant checking of structural integrity adds significantly to aircraft operational costs, and many aircraft structures are difficult to inspect even if proper procedures are followed. Because of the high cost and difficulties associated with manual inspection, it is desirable to automate the health monitoring process with a distributed sensing system.

Load History Recording

Load histories are usually recorded to obtain flight data for evaluating aircraft performance, modifying existing aircraft and designing new ones. Unfortunately, outfitting an aircraft with enough sensors to obtain useful data is very expensive. However if the same sensors could be utilized for detecting aircraft damage, large amounts of load history data could be collected economically. Such data would allow for the design of more efficient and safer aircraft structures.

5.1.2 Problem Statement

Health monitoring systems must be capable of detecting damage which results from a variety of causes, such as environmental factors, unusually high loads and human error. The most important causes of damage are fatigue and stress corrosion cracking. Damage to rivets, bolts and joints due to exposure and accidental damage is also important. Each of these problems is often intensified in aircraft which are subjected to unanticipated flight histories. One reason why damage detection is such a large problem is the small size of potentially catastrophic damage relative to the large size of the aircraft and the expense associated with sensing the damage (either with sensors or inspectors). Current damage detection methods use hand-held eddy current, x-ray, die penetration, magnetic resonance or ultrasonic sensors which are

costly, time consuming to use, or both.[131] Thus, there is a desire to automate the detection process using sensors which are unobtrusive, conformal and easy to install and maintain. Intelligent structures with distributed sensing elements is one way by which the desired automation may be achieved.

5.2 Technical Considerations

The fundamental technical issues associated with using intelligent structures for heath monitoring include what states of the structure need to be measured and how should they be sensed. These decisions should be made so that the time and cost required to determine the health of the structure are minimized.

5.2.1 Measurement Options

Most of the damage detection techniques which take advantage of smart materials measure strain to monitor structural health. Strain is either measured directly or inferred by a variety of sensors including piezoelectric transducers, fiber optics, accelerometers or displacement sensors. Some techniques make use of other measurements such as acoustic emission, pressure and electro-magnetic characteristics. The best measurement choice will depend on the particular technique employed (described in the following section), however piezoelectric and fiber optic strain measurements are the most widely used methods, especially in the context of smart material applications.

5.2.2 Damage Size and Sensor Coverage

The greatest challenge in damage detection results from the small size of damage which can significantly degrade performance and even lead to catastrophic failure. Small flaws must be detected before they grow to sizes which cause critical failures, and Saint Venant's principle dictates that the effects of such flaws can be measured only in the vicinity of the flaw itself (if local strain measurements are used to sense the state of the structure). Coupled with the large areas which must be monitored, the small scale over which damage must be detected leads to either very poor signal to noise ratios or the need for a cost prohibitive number of sensors. Such problems have motivated the use of area averaging techniques. However, these methods also have many associated problems as discussed below, such as determining the exact type and location of damage.

[131] Ricles, J.M. and Kosmatka, J.B., "Damage Detection in elastic Structures Using Vibratory Residual Forces and Weighted Sensitivity," AIAA Journal, Volume 30, Number 9, September 1992, pages 2310-2316.

5.3 Current Detection Methods

Currently, damage detection schemes which take advantage of intelligent structures can be classified in two broad classes: (1) microscopic detection which measures local strain over a fine grid of sensors and (2) macroscopic detection which measures acoustic emission or transfer function data averaged over large areas. Conceptual pictures of both schemes are provided in Figure 11.

5.3.1 Microscopic Detection

Discrete point sensing techniques employ fine grids of multiple sensors to detect the state of a structure and damage. The health of the structure is then determined by processing the vast quantities of information received from the sensors. The effectiveness of these schemes depends on the ability to implement fine sensor grids and post process the information received. Several researchers have investigated this technique with limited success even for simple examples. Kudva, Munir and Tan[132] explored the ability of neural networks to find one inch cracks in a 48 by 32 inch structure. This approach was usually able to detect the flaw but had difficulty determining its location. And, they found the scheme to be erratic and have difficulty converging at times. Schoenwald and Messinger[133] used swept radio frequency amplitude modulated reflections in fiber optics to identify flaws in a specimen subject to tensile loads. It was observed that the ability of the fiber optic sensors to detect flaws was highly dependent on the finite element model constructed to predict the strain distribution in their simple specimen.

Many other investigations have examined the use of fiber optics[134] [135] [136] [137] to detect strain in structures. Others have used discrete point sensors to predict global structural deformations.[138] [139] Generally, these researchers have enjoyed great success detecting strains and calculating global deformations. However the ability to detect strains at specific points cannot be easily extrapolated to a viable method for finding

[132]Kudva, J.N., Munir, N. and Tan, P., "Damage Detection in Smart Structures Using Neural Networks and Finite Element Analysis," Proceedings of the Active Materials and Adaptive Structures Conference, Alexandria, VA, November 1991, pp. 559-562.

[133]Schoenwald, J.S. and Messinger, R.H., "Combining Fiber Optics, Radio Frequency and Time Reflectiometry Techniques for Smart Structure Health Monitoring," Proceedings of the Active Materials and Adaptive Structures Conference, Alexandria, VA, November 1991, pages 889-894.

[134]Butter, C.D. and Hocker, G.B., "Fiber Optic Strain Gauge," Applied Optics, Volume 17, 1978, page 2867.

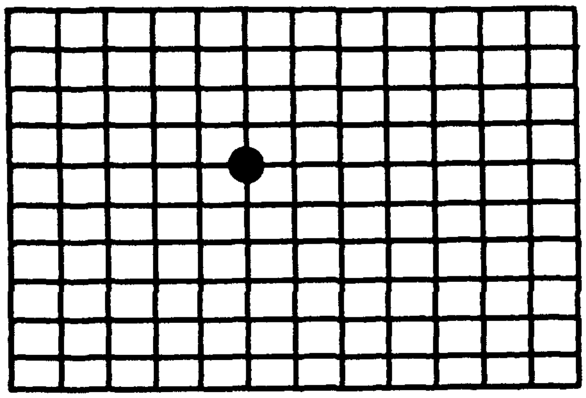
[135]Claus, R.O., Jackson, B.S. and Bennet, K.D., "Nondestructive Evaluation of Composite Materials by OTDR in Embedded Optical Fibers," Proceedings SPIE, Volume 566, 1985.

[136]Dunphy, J.R., Meltz, G. and Elkow, R.M., "Distributed Strain Sensing with a Twin-Core Fiber Optic Sensor," Instrument Society of America Transactions, Volume 26, 1987, page 7.

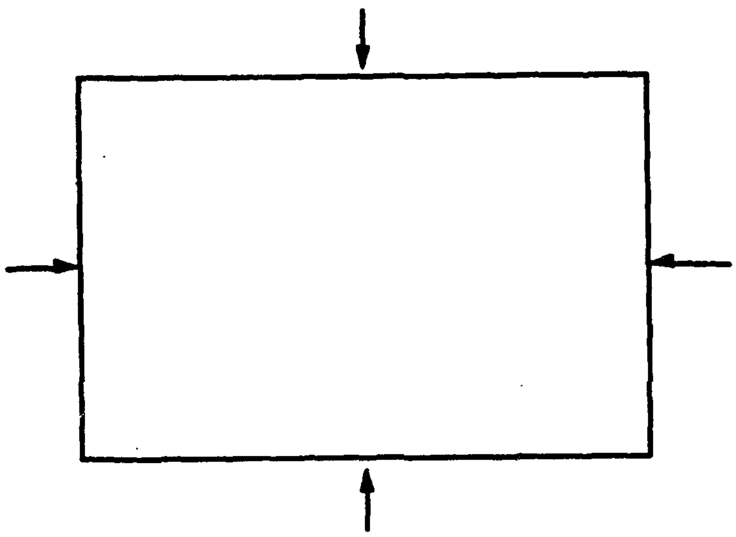
[137]Hale, K.F., "An Optical-Fibre Fatigue Crack-Detection and Monitoring System," Smart Materials and Structures, Volume 1, 1992, pages 156-161.

[138]Turner, R.D., Valis, T., Hogg, W.D., and Measures, R.M., "Fiber-Optic Strain Sensors for Smart Structures," J. of Intelligent Material Systems and Structures, Volume 1, April, 1990, pages157-174.

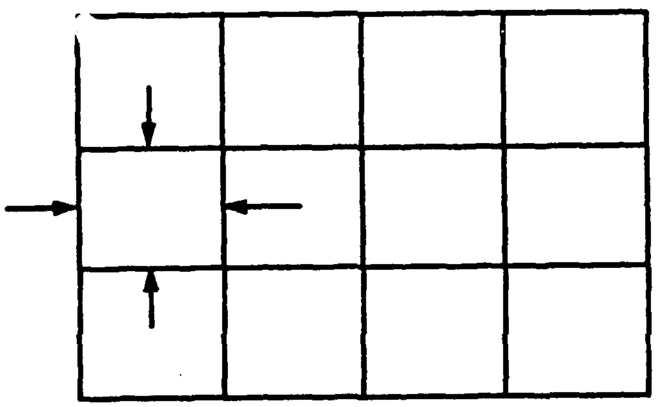
[139]Anderson, M.S. and Crawley, E.F., "Discrete Shaped Strain Sensors for Intelligent Structures," AIAA Paper 92-2406, Presented at the 33rd SDM Conference, Dallas, TX, April 1992.



Microscopic: Quadrant size on the order of critical flaw size.



Macroscopic: Quadrant size equal to the size of the structural component.



Mesoscopic: Quadrant size equal to that from which useful information (flaw type and location) can be obtained.

Figure 11: Conceptual microscopic, macroscopic, and mesoscopic damage detection schemes

small flaws in large structures, and little evidence has been offered which indicates that these techniques will help produce effective damage detection systems.

5.3.2 Macroscopic Detection

An alternative approach to the microscopic techniques described above is detecting damage by analyzing global area-averaged sensor information. This technique uses acoustic emission or transfer function data to infer changes in the mechanical characteristics of the structure and is often referred to as signature analysis.[140] Signatures can be assembled from discrete point sensors or measured directly using distributed sensing techniques.[141] Damage type and location data are obtained from the signatures by comparison with exemplar frequency response[142] or modal information. Signatures are compared with exemplar data to detect damage types and location using pattern recognition techniques such as neural networks. Gerardi and Hickman[143] used vibration signatures (frequency response shape, amplitude and distortion) to detect damage simulated by loose aircraft screws in a test panel. These researchers employed nearest neighbor and neural network schemes to analyze signatures for damage. The nearest neighbor technique was found to be much less effective than the neural network, which showed quite promising results. However, the panel was only 24 square inches and had only 8 screws. Similar success has yet to be shown for realistically sized structures. Further, area averaging schemes are typically able to detect damage, but seldom are able to determine the type of damage or its location.

[140]Hickman, G.A., Gerardi, J.J. and Feng, Y., "Application of Smart Structures to Aircraft Health Monitoring," J. of Intelligent Material Systems and Structures, Volume2, July 1991, pages411- 430.

[141]Collins, S.A., Miller, D.W., von Flotow, A.H., "Sensors for Structural Control Applications Using Piezoelectric Polymer Film," SERC Report Number 12-90, Massachusetts Institute of Technology, Cambridge, MA, 1990.

[142]Liu, K., Davis, A., Ohn, M.M., Park, B. and Measures, R.M., "Embedded Optical Fiber Sensors for Damage Detection and Cure Monitoring," Proceedings of the Active Materials and Adaptive Structures Conference, Alexandria, VA, November 1991, pages 395-398

[143]Gerardi and Hickman, *op. cit.*

6. Strategic R & D Plan

6.1 Strategic Plan for Smart Materials

Smart materials have proved to be an important technology and will continue to be so in the near and distant future. Therefore a commitment to supporting smart material research and development should be made. Support should be focused in the three main development areas of (1) basic materials, (2) component devices, and (3) modeling techniques. There is a need to develop basic smart materials with improved properties and characteristics. Some of the more important features to be improved include fatigue life, fracture toughness, structural weight, required voltage, linearity, and anisotropy. These materials should be developed in order to create improved intelligent structure component devices such as actuators and sensors. An emphasis should be placed on the use of actuator and sensor components for structural control. Finally, models need to be developed so that smart material components may be utilized effectively. Work is needed in developing constitutive relations as well as full non-linear models to meet these needs.

In order to expend limited resources efficiently, a consistent national plan for smart materials research is needed. The Air Force should coordinate its smart material development efforts with other government agencies. For example, there is no need to duplicate the Navy's strong commitment to the development of piezoceramics. Rather, an investment should be made in developing actuator components (piezoceramic as well as other materials) of intelligent structures for Air Force applications. If a basic materials development program is desired, the Air Force should consider materials which are not funded by other agencies. However, it is felt that the Air Force would benefit more from component and device development programs (with Air Force applications) than from the development of basic material which is already funded by other agencies and DARPA.

In the near future, it is expected that wide spread application of the current technology, (the present generation of actuators, sensors, processors and control methods) will occur. In addition, near term improvements are expected in these areas. The breadth of application of this technology is expected to span not only the aerospace industry, but become widespread in the home construction, automotive, and machine tool industries as well.

6.2 Smart Structure Component Technologies

Currently, all of the technologies needed for cost-effective application of smart structures technology have not been sufficiently developed at this time. There are a number of difficult problems which remain. Some of the more important of these problems are discussed below.

6.2.1 Better Actuation Materials

In order to truly achieve the desirable level of control effort for many structural applications, actuation materials which have 3 to 10 times larger strain than those currently commercially available must be developed. Or, materials similar to shape memory alloys, but with much higher bandwidth than currently available, should be developed. Alternatively, innovative uses of currently available materials, such as complex electrode patters which offer higher stains in piezoelectric devices, need to be investigated.

6.2.2 Optimized Sensors

There is a great deal of work to be done in the design and the optimization of sensors to alleviate such problems as spillover, and to focus control effort on the bandwidths of interest through selective observability of the structure.

6.2.3 Control Algorithms Which Inherently are Structural

Much of the theoretical work done for controlled-structures has been by control theoreticians who view the structure as an already discretized matrix system. However, structures are inherently distributed parameter systems and experience has shown that gains are made by considering this inherent distribution, as well as the inherent bandedness of structures in their parameterized form.

6.2.4 Distributed Control

The proper distribution of control between a lower level and a higher level systems is still a subject which needs to be developed more completely, so that stability is guaranteed while performance is maintained.

6.2.5 Power Conditioning and Switching

Although it is conceivable that signal level electronics can be highly distributed through a system, power conditioning and switching requires dissipation of some amount of energy. In order to make a feasible system, this power conditioning and switching must be done in way which minimizes the local heat load on the structure, so that the system can be embedded without thermally degrading the material.

6.2.6 Structurally Robust VLSI

Here the challenge is to take electronic components which are otherwise commercially available and develop innovative packaging techniques in which the interconnects to the silicon devices are structurally robust, so that these devices can survive the strain and fatigue environments of typical structures.

6.2.7 Minimized Impact on Host Structure

The presence of active elements (actuators, sensors and processors) has an impact on the host structure. These elements impact the host structure by increasing the mass of the system and interfering with the load path and potentially introducing new structural discontinuities which must be accommodated. This may potentially change the fatigue and fracture toughness characteristics of the host material.

6.2.8 The Hermicity of Embedded Components

The requirements for military electronic micro-devices are dominated by the need to keep the ambient chemical and humidity environment away from electrically active surfaces. Once these devices are embedded into a laminant, the challenge is to isolate these surfaces from both the ionic contamination of the structural matrix material and from the chemical and humidity environment of the ambient conditions, which can leak into the host material via the pathways created by the electrical connections.

6.2.9 Manufacturablity, Reliability and Repairability

These implementation questions include: What is the difficulty of manufacturing smart structures, what is their in-service liability, and how difficult is it (if possible at all) to repair such materials in service? Such issues will obviously have to be addressed before a widespread application of this technology is possible.

6.2.10 Smart Devices

Smart devices should be developed that incorporate smart structures component technologies into simple, functional units that can be incorporated into a structural design either during the initial design cycle, or as an add-on device to solve a problem late in the design cycle. One such device currently being developed under USAF contracts from Phillip's Lab are Modular Control Patches which use piezoelectric materials as the actuation device. TRW is developing this concept under a prime contract and CSA has a SBIR contract. These devices are currently being sized for outerspace applications. Perhaps such a device should also be sized for USAF aircraft applications using an alternate actuation material. Another smart device which may have widespread use in Air Force as well as commercial applications is a smart isolator, used either to attenuate narrowband or broadband disturbances, or enhance the isolation properties of passive soft mounts.

6.3 Neural Networks

Neural networks have become increasingly popular due to the success achieved in particular applications. It is felt that neural networks have the potential for solving many problems which cannot be address by traditional methods. One such application

is the control of structures with time-varying and non-linear properties. However, in order to realize such a capability, much analytical and experimental work is needed, and a rational plan for carrying out this work should be formalized. The plan should include a detailed assessment of the capabilities and limitations of neural network topologies and training methods, and the assessment should be carried out both experimentally and theoretically. This will require a shift in research focus from developing new types of networks to thoroughly understanding those which currently exist.

The experimental program, which will include both actual experiments and computer simulation, needs to focus on assessing the ability of different network types to perform the different controller functions listed in Table 4. Each should be assessed for particular application categories such as disturbance rejection, command following and stabilizing initially unstable systems. It is suggested that specific sample problems be chosen to allow for consistent comparisons between the multitude of network types. The theoretical program should focus on thoroughly understanding the behavior of neural networks in control applications, so that better design and analysis tools can be developed. Issues such as network stability and factors which effect training algorithm convergence should be emphasized. Efforts should be made to develop unified frameworks for analyzing neural networks. Although this is a formidable task, some progress has already been made in developing unified analysis techniques for feedforward and recurrent networks.[144]

Based on the results of the experimental and analytical programs, the techniques which show the most promise for structural control should be selected and pursued vigorously in research and development programs. These programs should emphasize applications through experiment and simulation. At first, control applications should be chosen which require functionality similar to those for which neural networks have traditionally been effective. For example, the functionalities needed for system identification and parameter estimation have more in common with target recognition (a proven capability) than gain selection for disturbance rejection. The later stages of the development program will then concentrate on the less proven functionalities.

This research and development plan should emphasize two specific objectives. The first is to answer the basic question: Is neural based control a valid option for the control of flexible structures? This question should be answered both qualitatively (through theoretical work) and quantitatively (by experimentation and simulation), and should address problems of realistic complexity. In addition, hardware implementation issues should be considered. The second objective, assuming an affirmative answer to the question posed in the first objective, should be to internalize this technology. Therefore, a strategy needs to be formulated for slowly and pragmatically internalizing the ability to synthesis effective neural networks for controlling Air Force structures.

[144]Narendra, K.S. and Parthasarathy, K., "Identification and Control of Dynamical Systems Using Neural Networks," IEEE Transactions on Neural Networks, Volume 1 Number 1, March 1990, pages 4-27.

6.4 Health Monitoring

As indicated by the limited success shown to date, a research and development plan is needed which will enable the effective use of smart materials and structures technology in health monitoring and damage detection applications. The first step of the research and development plan should be to assess current Air Force needs and near term application requirements for damage detection. The next step is to perform an assessment of the current technical status of damage detection methods. This assessment should detail the advantages and disadvantages of the current methods and determine which method or methods have the potential for identifying damage (are capable of the required signal to noise ratios) in Air Force structures. An investment should then be made in areas which show the most promise for achieving satisfactory damage detection signal to noise ratios in full scale structures. A potentially inexpensive near-term approach is to design a health-monitoring system that can locate a damaged area and inform human maintenance personnel. The type and extent of damage can then be determined manually. The system would not be totally smart, but the potential savings from decreased number of maintenance inspections should justify the application.

In the final development stages, successful concepts will be selected, combined and focused for system development. It is expected that practical systems will combine both microscopic and macroscopic detection schemes in a unified mesoscopic approach. A conceptual diagram of the mesoscopic approach is displayed in Figure 11. This method uses a grid of sensors for damage detection, but does not require the grid to be fine enough (on the order of critical crack sizes) to detect flaws. Rather, the mesoscopic approach will use area averaging signature evaluation techniques to locate damage in each quadrant. However, the size of each quadrant will be limited to a size from which flaw type and location information can be easily extracted. The fundamental intellectual question associated with the design of mesoscopic damage detection systems will involve determining the optimal quadrant size. And, the optimal quadrant size will depend on both the critical flaw size of the material being used and the power of the signature analysis routines available.

6.5 Potential USAF Applications

Eleven specific problems with Air Force aircraft structures and weapons systems were found which had the potential for being alleviated or reduced by application of smart structures technologies. The problems are listed in Table 5 and are described, along with potential solutions, below:

Twin Tail Buffet. Buffeting of the F-18 and F-15 twin tails is encountered due to aeroelastically induced damping reduction. Because of the size of the tails, the frequencies are generally outside the range which can be controlled with conventional articulated control surfaces. In addition, the aerodynamics are extremely difficult to model because of transonic effects and multiple lifting surface interactions. These features combine to make this problem an excellent candidate for the application of

Table 5: List of Air Force problems

Problem	System	Control Issue	Priority	Contact
Twin Tail Buffet	F-18 / F-15	Regulation, Damping	High	Terry Harris,FIBR
Acoustic Cavity	B1	Disturbance, Rejection	High	Len Shaw
Wing/Store Flutter	F-16	Regulation, Stability	Low	Terry Harris, Rudy Yurkovich
Laser Designator Jitter		Pointing	Medium	Greg Agnes
Laser Weapon Jitter	Airborne Laser (ABL)	Pointing	Low	Randy Mackaman
Conformal Antenna/Radar	E-8	Shape Control	High	Mark Ewing
Avionics Vibration	B1 Aft Equipment Bay	Isolation	High	Len Shaw
Sonic Fatigue		Regulation	Medium	Len Shaw
Runway Roughness		Disturbance Rejection	?	
Gust/Load Alleviation		Disturbance Rejection	?	Lazarus
Airfoil Shape Control		Shape Control	?	Lazarus

smart structures technologies, particularly distributed actuation, bandwidth sensitive distributed sensors, and local controllers with senuating algorithms.

Acoustic Cavity Oscillation. Acoustic cavity oscillations are caused by vortex shedding at the cavity edges and excitation of the cavity harmonics. The problem is complicated by difficulties modeling the unsteady vortex shedding. This problem may potentially be solved by feeding forward the sensed vortex disturbance and using piezoceramic actuators which can control the high frequency acoustic disturbances.

Wing/Store Flutter. Wing/Store flutter is similar to classical wing flutter, except the dominant modes are heavily influenced by the stores. This complicated the problem due to the variable configuration, weight and shape of the stores. Solutions will need to make use of either adaptive algorithms or reconfigurable distributed sensors and actuators.

Laser Designator Jitter. This problem is encountered by pilots attempting to point weapon systems at targets. The problem is essentially one of quasi-static pointing, however disturbance vibrations have been found to be significant in the pilot-pointing bandwidth. Active isolation techniques have great potential for alleviating this problem.

Conformal Antenna/Radar Shape Control. Conformal Antenna/Radar operate most efficiently when large and precisely shaped. However, integrating these devices in inherently flexible structures is problematic. The precise shape of the structure (wings or fuselage) cannot be predicted without knowing in advance every disturbance force, flight control input, and flight parameter. Such problems make

this system and attractive candidate for active control with distributed actuators and sensors and multiple level (local and global) control.

Avionics Vibration Isolation. Disturbance of various types cause problems with the operation of sensitive avionics. It would be desirable to isolate sensitive instruments from normal aircraft disturbance to increase performance and life. Active isolation techniques may be able to solve this problem.

Sonic Fatigue. Structure-borne noise and other acoustic disturbances cause structures to vibrate and, over time, fatigue. This problem is accentuated when aircraft operate at, and above, sonic speeds. It would be beneficial to reduce the effects of acoustic disturbances in the sonic regime.

Runway Roughness Vibration. On take-off, runway roughness causes considerable vibrations to be transmitted to the aircraft. Currently the benefits of suspension damping treatments cannot be justified in light of the added weight of such systems. However, simple active isolation systems which make use of sensuating devices and local control may help alleviate transmitted forces.

Gust/Load Alleviation. Atmospheric disturbance and maneuvers cause large loads in aircraft structures. Currently, structural strength is engineered on a worst-case basis, making designs conservative in all other situations. In addition, random gust disturbances hinder the pilot's ability to control the aircraft precisely. Therefore, it would be desirable to actively control the wing loading distribution due to gusts and piot commands. Distributed strain actuators and global control algorithms offer the potential for controlling such loads in lifting surfaces.

Airfoil Shape Control. Optimal lifting surface performance is highly dependent on wing shape, airspeed, and maneuvers. Currently, the airfoil shape is altered via flapperons or flaps. However, these devices generally have bandwidths below those of typical of maneuver-induced vibrations which alter the airfoil shape. In addition, flapperons or flaps offer shape control only at a limited number of discrete points. Additional shape control can be obtained from distributed strain actuators and global controllers.